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REPORT ON THE POTOMAC RIVER BASIN STUDIES. TECHNICAL APPENDIX TO PART VII. REPORT ON NEEDS FOR WATER SUPPLY AND FLOW REGULATION FOR QUALITY CONTROL IN THE WASHINGTON STANDARD METROPOLITAN AREA

Public Health Service
Charlottesville, Virginia

August 1962

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TECHNICAL APPENDIX

to

PART VII

of the

REPORT ON THE POTOMAC RIVER BASIN STUDIES

Report on Needs for Water Supply and Flow Regulation for Quality Control in the Washington Standard Metropolitan Area

Prepared in Cooperation with the
District Engineer, Washington District
Corps of Engineers, U. S. Army

U. S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Bureau of State Services
FWQA Division of Water Supply and Pollution Control

Region III, Charlottesville, Virginia
and
Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

August 1962

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This study was performed at the request of the Corps of Engineers as a part of the comprehensive study of the water resources of the Potomac River Basin. The purpose was to determine the effect of the discharge of the Potomac River on the waste assimilation capacity of the river system at and near Washington, D.C. The river at this point has a tidal range of about 3 feet, but is above the region of noticeable salt intrusion. River discharges are swallowed up in the tidal system; water motion in this region is dominated by the tide. Wastes discharged near Washington remain in the vicinity for some time; large quantities of oxygen are consumed, and a vast supply of nutrient materials are provided for aquatic organisms. A large part of these wastes must be satisfied in the upper reaches of the Potomac Estuary.

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Cincinnati, Ohio

August 1962

INTRODUCTION

(This study was performed at the request of the Corps of Engineers as part of a comprehensive study of the water resources of the Potomac River Basin. The purpose of this phase of the study was to determine the effect of the discharge of the Potomac River on the waste assimilation capacity of the river system at and near Washington, D. C.

This is a highly complex system. The river at this point has a tidal range of about 3 feet, but is above the region of noticeable salt intrusion. The river discharges (except at very high flows) are swallowed up in the tidal system; water motion in this region is dominated by the tide. Wastes discharged near Washington remain in the vicinity for some time; during this time large quantities of oxygen are consumed and a vast supply of nutrient materials are provided for aquatic organisms. Some of the waste load may be passed on toward the sea, but a large part of the oxygen demand of these wastes must be satisfied in the upper reaches of the Potomac Estuary) principally in the reach from Georgetown to Alexandria.

This region has been sampled routinely since 1937 by the District of Columbia sewage treatment plant. Samples have been taken on a weekly to monthly basis at several stations since that time. Attempts to correlate these data with river discharge have not been successful. This is not surprising since the system is obviously dominated by the semidiurnal tidal effects, and the sampling interval is much too long to provide information about these effects. An examination of the data also showed that conditions changed quite rapidly in this part of the estuary; so rapidly that any assumptions of steady-state conditions would not have a sufficient degree of validity.

In view of the presently inadequate theoretical knowledge of such systems, the nonexistent engineering practice, and the inapplicability of statistical statics to the presently available data, it was decided to design a field survey so that the principles of statistical dynamics could be used. While statistical statics requires that a body of data be treated as a unit, statistical dynamics permits the examination of the time variations of a body of data. The latter procedure has the same advantages in studying time-varying systems that the principles of fluid dynamics have over those of fluid statics in studying fluid motion. The present theoretical basis of statistical dynamics requires that severe restrictions be placed on the type of data usable for analysis. These restrictions are reflected primarily in the requirements of uniformity and size of the sampling interval, and in the number of samples that are necessary to obtain stable results.

On occasion, it has been necessary to include brief descriptions of the statistical tehchniques involved. This has been done to clarify points involved in the interpretation of results, and such discussions are necessarily qualitative. The full details of the procedures used are presented in the references cited.

The results presented in this report do not represent a complete analysis of all the data obtained during the field survey. The conclusions are based in detailed examination of the D.O. and BOD in the river as influenced by the waste loads discharged, river discharge, and sunlight intensity. Where feasible, the additional data have been processed by the same techniques as the records discussed in this report; their effects were dominated by the parameters discussed here. The data are not included because they contribute little additional information to the main purpose of this report.

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SUMMARY

1. The waste assimilation capacity of the Potomac Estuary in the vicinity of Washington, D. C., has been estimated as a function of river discharge.
2. Because of the importance of a variety of short-period effects, a field survey was designed and executed in a manner suitable for the utilization of the principles of statistical dynamics.
3. The data analysis was built upon the spectral analysis of the field survey records of dissolved oxygen, biochemical oxygen demand, sunlight, waste discharge, temperature, and river discharge.
4. The techniques used were sufficiently sensitive to resolve the effects of sunlight and biochemical oxygen demand on the dissolved oxygen records.
5. The effect of sunlight was found to be proportional to the stream biochemical oxygen demand. This is attributed to algal production and consumption of oxygen and to changes in algal populations.
6. The nonlinearity of the tide-river discharge combination was observed. The effects of tide and of river discharge on the dissolved oxygen were considered as a unit.

7. The waste assimilation capacity was estimated by assuming that the biochemical oxygen demand (after correction for algal effects), sunlight, and tide-river discharge acted on the dissolved oxygen independently of each other, and that the sum of the individual effects represented the total effect.

8. For the survey period only, the waste assimilation capacity was estimated from the equation:

$$C = 1.01\,Q + 2.36 - 1.73\,W$$

where:

C = mean D.O. in ppm,

Q = river discharge in 10^3 cfs, and

W = daily 5-day BOD load in 10^5 pounds per day.

This equation was derived empirically from the field study results and is of limited applicability.

9. From the waste assimilation capacities for the survey period, reaeration rate constants, k_2, were computed for a range of discharges; these results and deoxygenation rate constants, k_1, evaluated from long-term BOD data, were used to determine the waste assimilation capacity at various temperatures and river discharges. The oxygen-sag equation formed the basis for computation.

10. Waste assimilation capacitites for a daily mean minimum D.O. of 4.0 and 3.0 ppm were computed for a temperature range of 2 to 29°C. and a river discharge range of 800 to 5,000 cfs.

DESCRIPTION OF THE FIELD STUDY

GENERAL

The field operations were conducted in July and August 1959. During the first week the sampling and laboratory facilities were made operable and an exploratory reconnaissance of the river was made; during the second week a series of temperature and D.O. cross-sectional measurements at 14 river stations were taken and some long-term BOD's were set up. From August 6 through August 29, the time series constituting the main body of data were run. Operations were concluded by further temperature and D.O. cross sections after the time series were completed. Some other samples were also taken.

All sampling was carried out by Public Health Service personnel operating from outboard motorboats. Two sampling teams, each comprised of two men, were available.

All samples were taken with Sargent samplers except for the bacteriological samples which were taken just below the surface with sterile bottles. BOD and bacteriological samples were iced immediately after being taken and were kept on ice until they reached the laboratory. D.O. samples were dosed immediately through the final step, and were kept dark (but not iced) until they reached the laboratory.

D.O. and BOD determinations were performed on a 24-hour basis by three PHS chemists operating in a Public Health Service mobile laboratory. Resources Research, Incorporated, a consulting firm retained by the Government of the District of Columbia, ran MF coliform counts, algae counts, and concentrations of solids, phosphates, and turbidities on the time series samples.

INITIAL AND FINAL PHASES

Temperature and D.O. Cross Sections

Fourteen locations from the Three Sisters Island to Fort Washington were sampled twice before the main sampling program was begun. The purpose of this procedure was to determine what amount of stratification existed in the sampling region. Some of the sections sampled are shown in Figure 1. From each section, 7 to 14, samples were taken depending on the size of the section. The temperature and D.O. of each sample were measured. These results are presented in Table I and a typical section is shown in Figure 2. Each section was sampled once during the ebbing tide and once during the flooding tide. The total time required for sampling each section was about 20 minutes, but varied according to the size of the section. This entire procedure was repeated for all except one section after the main sampling program was concluded.

The results of this phase of the study showed that no strong and coherent pattern of stratification could be postulated for this reach of the

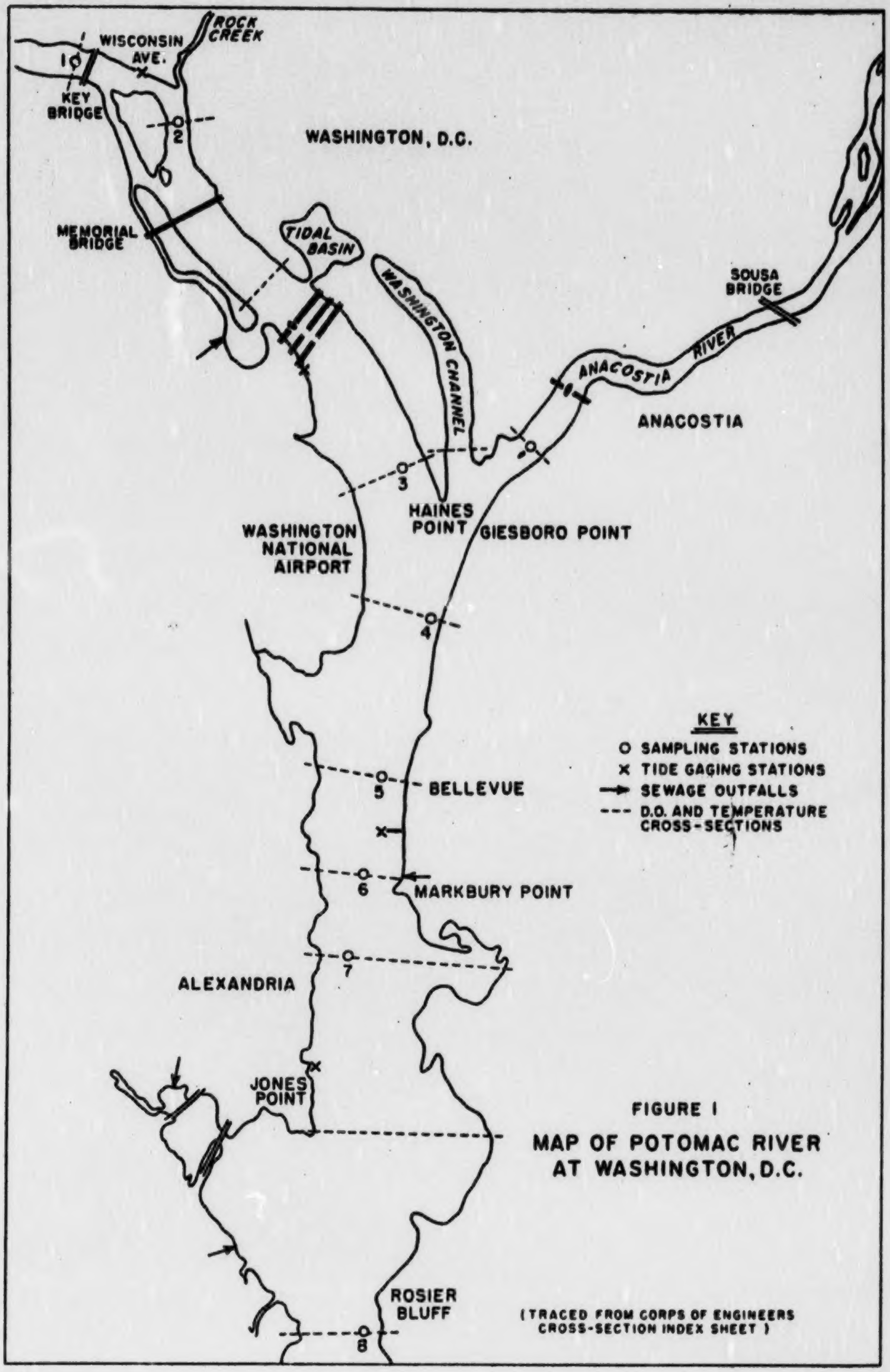
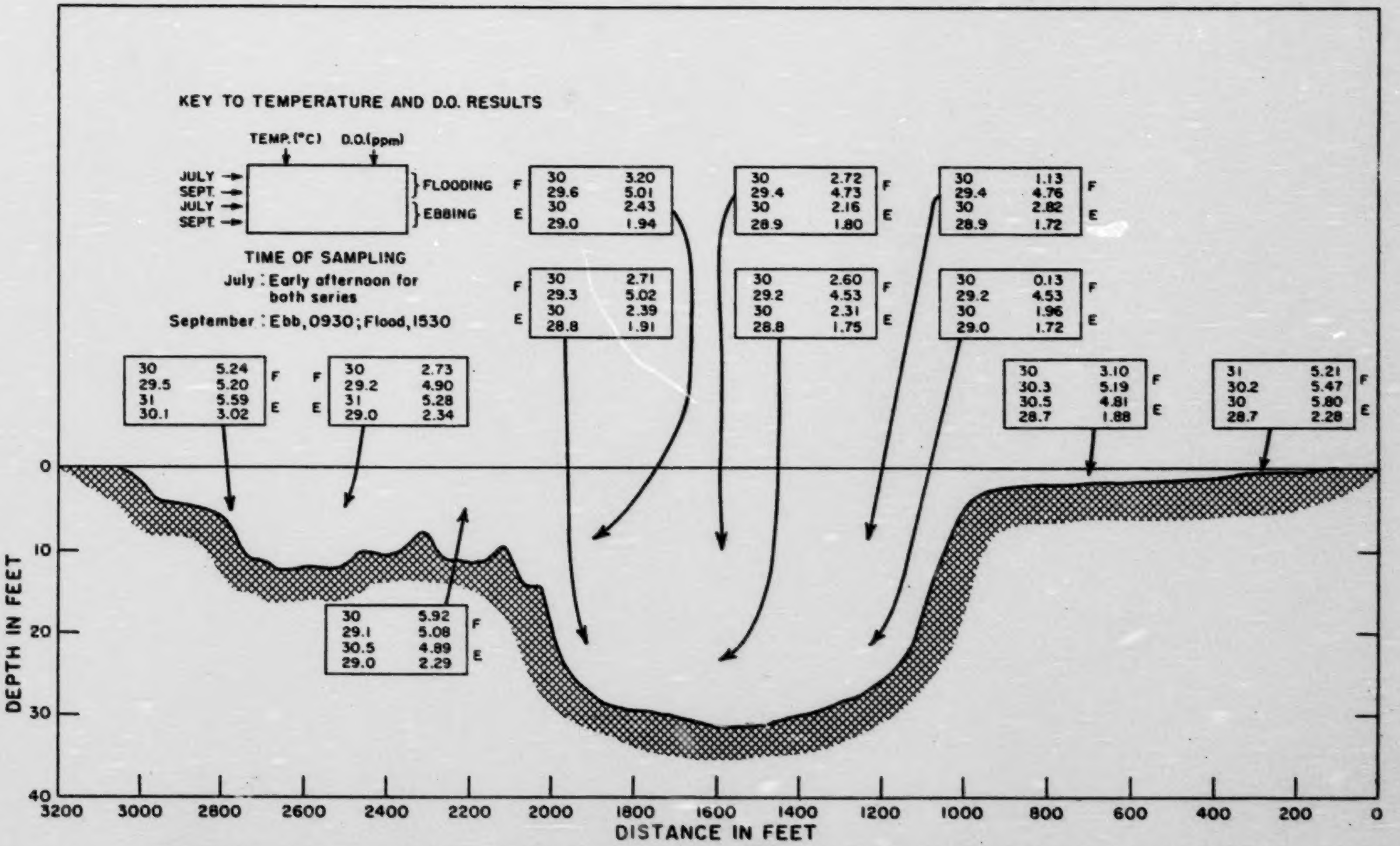

ROCK CREEK
WISCONSIN AVE.
KEY BRIDGE
1
2
WASHINGTON, D.C.
MEMORIAL BRIDGE
TIDAL BASIN
WASHINGTON CHANNEL
SOUSA BRIDGE
ANACOSTIA RIVER
ANACOSTIA
3
HAINES POINT
GIESBORO POINT
WASHINGTON NATIONAL AIRPORT
4
KEY
○ SAMPLING STATIONS
× TIDE GAGING STATIONS
→ SEWAGE OUTFALLS
--- D.O. AND TEMPERATURE CROSS-SECTIONS
5
BELLEVUE
6
MARKBURY POINT
7
ALEXANDRIA
JONES POINT
ROSIER BLUFF
8

FIGURE I

MAP OF POTOMAC RIVER AT WASHINGTON, D.C.

(TRACED FROM CORPS OF ENGINEERS CROSS-SECTION INDEX SHEET)



TYPICAL CROSS-SECTION OF POTOMAC RIVER AT WASHINGTON D.C. (STATION 6)

FIGURE 2

Table I

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)
a. Washington Channel									
Out of Channel, 75 ft left	5	30	3.89	29	3.95	29.3	3.11	30.6	2.71
In Channel, left side	9	30	4.02	30	3.87	29.2	3.34	30.0	3.41
	18	30	3.79	29	2.63	29.0	4.17	29.3	3.19
In Channel, center	9	30	2.41	30	4.13	29.2	3.23	30.0	3.33
	18	30	3.32	30	3.37	28.9	3.99	30.0	3.55
In Channel, right side	9	30.5	3.49	30	3.99	29.1	3.21	30.0	3.70
	18	30.5	2.96	30	3.43	29.0	3.95	29.8	3.59
Out of Channel, 75 ft right	5	30.5	3.59	30	4.72	29.3	2.70	30.2	3.51
b. Station 0									
Out of Channel, 100 ft right	5	30	1.31	30	2.34	29.5	2.62	31.5	1.32
In Channel, right side	8	30	1.25	30	2.69	29.1	3.44	31.1	1.19
	16	30	2.89	30	3.03	28.9	4.27	30.5	1.88
In Channel, center	8	30	1.24	---	---	29.4	3.02	31.0	1.37
	16	30	2.71	30	3.19	28.9	4.17	30.4	1.76
In Channel, left side	8	30	1.19	30	3.07	29.5	2.72	31.0	1.56
	16	30	2.71	30	2.93	29.0	4.04	30.8	1.70
c. Station 1									
Out of Channel, 200 ft right	5	29	6.83	29.5	6.83	29.0	7.16	28.1	5.84
In Channel, right side	5	29	6.62	29.5	6.69	29.0	7.12	28.1	5.73
	10	29	6.77	29.5	6.11	28.8	5.36	28.1	6.03
In Channel, center	5	29	6.73	30	---	29.0	6.25	28.1	6.20
	10	29	6.65	30	6.60	28.4	7.32	28.2	6.08
In Channel, left side	5	29	6.28	30	6.71	28.6	6.85	28.0	5.78
	10	29	6.43	29.5	6.47	28.3	6.54	28.4	5.76
Out of Channel, 200 ft left	5	29	6.66	30	6.74	28.3	7.21	28.0	5.47

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)
d. Station 2									
Out of Channel, 100 ft left	4	30	7.19	29	6.29	28.9	6.53	28.3	5.75
In Channel, left side	8	29	6.91	29	6.21	28.5	5.60	28.1	5.77
	16	29	6.69	29	6.01	28.4	5.08	28.2	5.77
	24	29	5.69	29	5.49	28.3	5.28	28.4	5.23
In Channel, center	8	29	6.92	29	6.22	28.4	5.78	28.4	5.65
	16	29	5.88	29	6.24	28.4	5.48	28.3	5.63
	24	29	5.21	---	---	28.6	5.41	28.3	5.29
In Channel, right side	8	29	6.48	29	6.33	28.9	5.96	28.4	5.69
	16	29	6.22	29	5.58	29.2	5.17	28.4	5.44
	24	---	---	29	5.30	28.6	5.15	---	---
e. Station 2.5									
Out of Channel, 1400 ft right	1	28	5.89	29.5	5.68	28.8	8.50	27.9	5.16
Out of Channel, 1000 ft right	4	28	4.91	29.5	5.64	28.7	6.00	28.0	4.79
Out of Channel, 500 ft right	5	28	4.80	29.5	5.49	28.5	5.20	28.0	4.45
In Channel, right side	5	29	4.77	29	5.66	28.5	4.82	28.0	4.70
	10	28	4.58	29	5.60	28.2	3.98	28.0	4.78
In Channel, center	5	28	4.84	29	5.73	28.4	4.75	28.0	4.59
	10	29	4.30	29	5.74	28.4	4.37	28.0	4.57
In Channel, left side	5	29	4.91	29.5	5.79	28.2	4.16	28.0	4.39
	10	28	4.69	29.5	5.66	28.4	3.78	28.0	4.40
Out of Channel, 100 ft left	5	28	5.00	29.5	5.93	28.5	5.04	27.8	4.57

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)
f. Station 3									
Out of Channel, 200 ft right	2	30	3.53	29.5	3.65	28.2	4.49	29.5	5.90
In Channel, right side	9	29	4.18	29.5	5.26	28.5	4.46	28.5	5.98
	18	29	4.88	29	4.60	28.2	4.46	28.4	4.58
In Channel, center	9	29	4.71	29.5	---	28.4	4.53	28.5	5.59
	18	28	4.80	29.5	5.26	28.1	4.55	28.4	4.85
In Channel, left side	9	29	4.52	29.5	5.06	28.4	4.76	28.4	5.34
	18	28	4.55	29.5	5.11	28.2	4.66	28.3	4.37
Out of Channel, 300 ft left	5	29	4.20	29.5	5.26	28.1	4.72	28.4	5.16
Out of Channel, 600 ft left	4	29	5.26	29.5	5.15	27.9	5.04	28.4	5.18
g. Station 4									
In Channel, right side	9	29	3.79	30	3.39	29.1	4.03	29.1	3.06
	18	29	3.47	30	2.94	29.1	3.41	29.0	2.87
	27	29	3.96	30	3.72	29.1	3.21	28.8	3.00
In Channel, center	9	28	2.58	30	3.83	29.3	5.08	28.8	3.13
	18	28	1.82	30	3.95	29.3	3.66	28.7	2.97
	27	28	1.95	30	3.93	29.0	3.39	28.9	2.93
In Channel, left side	9	29	2.80	30	4.00	29.0	3.89	28.9	3.32
	18	29	2.71	30.5	4.18	29.2	3.41	29.0	3.29
	27	28	2.52	30	4.19	28.8	3.33	28.9	3.44
Out of Channel, 400 ft left	2	29	3.56	30	---	29.3	5.34	28.2	4.46

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(^{o}C)	D.O.(ppm)	Temp.(^{o}C)	D.O.(ppm)	Temp(^{o}C)	D.O.(ppm)	Temp.(^{o}C)	D.O.(ppm)
h. Station 5									
Out of Channel, 300 ft right	5	30	0.89	30	2.62	29.6	4.91	28.7	2.10
In Channel, right side	9	30	0.67	29.5	2.68	29.0	4.50	28.9	1.96
	18	30	0.67	29.5	2.89	28.9	4.65	28.8	2.02
In Channel, center	9	30	1.00	29.5	2.69	29.0	6.91	28.7	1.91
	18	30	1.20	29.5	2.68	28.9	6.54	28.8	2.09
In Channel, left side	9	30	0.96	29.5	2.74	29.2	6.91	28.8	2.94
	18	30	0.95	29.5	2.87	29.3	5.77	28.7	3.07
Out of Channel, 200 ft left	5	30	1.36	29.5	3.05	29.4	7.37	28.7	2.95
700 ft left	1	30	2.65	30	5.17	29.6	9.27	29.0	3.14
1200 ft left	3	30	1.68	29.5	3.18	29.3	6.76	28.8	2.93
1700 ft left	3	30	2.17	30	3.95	28.9	4.21	28.5	1.63
i. Station 6									
Out of Channel, 1000 ft right	1	31	5.80	31	5.21	30.2	5.47	28.7	2.26
500 ft right	1	30.5	4.81	30	3.10	30.3	5.19	28.7	1.88
In Channel, right side	10	30	2.82	30	1.13	29.4	4.76	28.9	1.72
	20	30	1.96	30	0.13	29.9	3.95	29.0	1.72
In Channel, center	10	30	2.16	---	2.72	29.4	4.73	28.9	1.80
	20	30	2.31	30	2.60	29.2	4.53	28.8	1.75
In Channel, left side	10	30	2.43	30	3.20	29.6	5.01	29.0	1.94
	20	30	2.39	30	2.71	29.3	5.02	28.8	1.91
Out of Channel, 250 ft left	5	30.5	4.89	30	5.92	29.1	5.08	29.0	2.29
500 ft left	5	31	5.28	30	2.73	29.2	4.90	29.0	2.34
750 ft left	5	31	5.59	30	5.27	29.5	5.20	30.1	3.02

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)
j. Station 7									
Out of Channel, 300 ft right	5	30	2.52	30	3.23	30.0	4.80	29.2	2.40
In Channel, right side	9	31	2.92	30	1.28	29.2	4.38	29.0	2.24
	18	30	2.71	29.5	1.64	28.9	3.92	28.9	2.05
In Channel, center	9	30	1.71	29.5	2.29	29.0	4.37	29.0	2.22
	18	30.5	1.95	29.5	2.58	28.9	4.35	29.0	1.80
In Channel, left side	9	30.5	3.97	29.5	2.72	29.4	4.62	29.0	2.19
	18	31	2.56	30	2.84	29.3	4.56	29.0	1.80
Out of Channel, 100 ft left	5	30.5	4.32	29.5	2.20	29.5	---	29.0	2.12
k. Station 7.5									
Out of Channel, 2900 ft right	5	31	4.61	29.5	3.84	29.3	2.09	28.7	2.09
2500 ft right	5	30.5	6.65	29.5	3.18	29.5	1.87	28.6	1.87
2000 ft right	5	30	4.14	29	1.95	29.3	1.93	29.1	1.93
1500 ft right	2	30	2.71	29.5	2.22	29.4	1.73	28.7	1.73
1000 ft right	1	30	3.99	29.5	2.71	29.9	2.04	28.5	2.04
500 ft right	1	30	4.68	30	1.84	29.5	1.78	28.9	1.78
In Channel, right side	10	30	4.60	30	1.13	29.2	2.00	28.9	2.00
	20	30	4.00	29.5	1.29	29.0	2.02	28.8	2.02
In Channel, center	10	30	2.69	29.5	1.36	29.0	2.34	29.0	2.34
	20	30	2.44	29.5	1.18	28.9	2.56	29.0	2.56
In Channel, left side	10	30	2.05	29.5	1.34	29.1	3.14	29.0	3.14
	20	30	3.11	29.5	1.23	29.0	2.38	29.0	2.38
Out of Channel, 300 ft left	5	31	3.55	30	1.66	29.9	2.93	29.0	2.93

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp.(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)
l. Station 8									
In Channel, right side	8	29	2.70	30	1.90	29.3	3.03	28.8	2.29
	16	29	3.12	30	1.89	29.8	2.53	29.0	2.18
	24	29	3.46	30	1.92	29.1	2.15	28.9	2.16
In Channel, center	8	29.5	2.41	---	---	29.4	1.88	28.6	1.80
	16	29	2.27	30	2.13	29.1	1.89	28.8	1.79
	24	29	2.40	---	---	29.1	1.83	28.7	1.79
In Channel, left side	8	29	2.35	30	2.20	29.5	2.04	28.9	1.79
	16	29	2.18	30	2.19	29.1	1.71	28.8	1.71
	24	29	2.21	30	2.02	29.4	1.81	28.8	1.70
Out of Channel, 100 ft left	1	29	3.10	30	2.33	29.4	3.18	28.6	2.40
500 ft left	1	29	3.49	29.5	2.25	29.4	3.12	28.6	2.18
1000 ft left	1	29	4.30	29.5	2.16	29.0	3.88	28.5	2.37
1500 ft left	1	29	4.21	29.5	2.06	29.0	4.40	28.6	2.47
2000 ft left	1	29	4.00	29.5	2.78	28.9	4.90	28.4	2.86
m. Wellington (Buoy 84)									
Out of Channel, 500 ft right	5	30	3.60	29	6.26				
300 ft right	5	30	3.98	29	3.44				
In Channel, right side	10	30	2.68	29.5	2.40				
	20	30	2.72	29.5	2.50				
In Channel, center	10	30	2.60	29.5	2.35				
	20	30	2.60	29.5	2.34				
In Channel, left side	10	30	2.45	29.5	2.34				
	20	30	2.30	29	2.45				
Out of Channel, 250 ft left	5	30	3.75	29.5	3.63				
400 ft left	1	30	3.90	29	4.64				

Table I (Continued)

Results of Temperature and Dissolved Oxygen Cross Sections

Location	Depth (ft)	Before Main Program				After Main Program			
		Flood Tide		Ebb Tide		Flood Tide		Ebb Tide	
		Temp(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)	Temp(°C)	D.O.(ppm)
n. Fort Washington									
In Channel, right side	5	28.5	3.17	29	2.44	28.9	4.70	29.0	2.79
	25	28	3.06	29.5	2.59	28.7	4.49	28.5	2.90
	50	28	3.02	29.5	2.70	28.8	4.37	28.5	3.02
In Channel, center	5	28.5	3.39	---	---	28.9	4.82	28.5	3.00
	25	28	3.30	29.5	2.49	28.6	3.23	28.5	3.18
	50	28	3.39	---	---	28.6	3.30	28.4	3.13
In Channel, left side	5	28.5	2.70	29.5	2.74	28.9	4.37	28.5	2.51
	25	28.5	2.60	29.5	2.42	28.5	3.43	28.4	2.61
	50	28.5	2.62	29.5	2.63	28.6	2.75	28.5	2.74
Out of Channel, 100 ft left	1	28.5	3.73	29.5	2.50	28.9	4.77	28.7	3.34
300 ft left	1	29	3.75	29.5	2.70	29.1	6.81	28.8	3.97

river. While there were differences in D.O. and temperature across a given section, they were generally not consistent and were mostly within the ranges of sampling variability. Because of these findings, it was decided to take each sample for the time series data at midchannel and middepth. This does not involve the assumption that these samples will be representative of each cross section. The assumption is made, however, that the nine points chosen for sampling are as representative of the over-all conditions in the estuary as would be any other nine points that could have been chosen.

Biological Study

Near the close of the main sampling program, a Public Health Service biologist made a brief survey of the bottom biota of the reach being studied. These findings are presented as the Supplement to this report. The results generally indicate that the biota are those associated with a high degree of pollution. Sludge banks were found in the vicinity of sewage outfalls and near the mouth of Rock Creek.

Slack Tide Sampling

In order to determine the locations of the maximum pollution areas at slack tides, two slack tide runs up the river were made at the close of the survey. On these runs a series of midchannel, middepth samples were taken as the boat rode the slack tide upriver. This is the "same-slack" technique as proposed by Kaplovsky. The temperature, D.O., and BOD of each sample were measured. On ebb slack a run was begun at Fort Washington and proceeded to Fort Foote before the slack was lost. On flood slack a run was begun at Giesboro Point and proceeded up the Anacostia to the Sousa Bridge before the slack was lost. Both runs were made in the daytime on a very sunny day.

The greatest BOD at ebb slack was found about halfway between Fort Foote and Fort Washington, corresponding generally to the limits of a tidal excursion from the Blue Plains outfall. At flood slack BOD increased from Giesboro Point all the way to the Sousa Bridge; this is well beyond the limits of a tidal excursion from the Blue Plains outfall.

TIME SERIES SAMPLING OF RIVER STATIONS

Time series sampling constituted the main body of the data gathered and was designed so that the techniques of statistical dynamics could be applied to the resulting data. The restrictions imposed on the sampling by the use of this technique are discussed in a later section.

One sample at midchannel and middepth is regarded as reasonably representative of events occurring in the general region of the sample. All samples at any one station were taken at the same position in the cross section so that the records secured at each station are at least representative of occurrences at a single point in the system, if not at a single cross section or in a single slug of water. The sampling stations were chosen to conform with those used by the District of Columbia sewage treatment plant, since, after study of the cross section records and outfall locations, it was felt that these stations provided an adequate coverage of the reach under study.

The time interval between successive samples at a given station was set at 4 hours, and with the personnel and equipment available, this meant that nine river stations could be sampled. Those stations finally selected are shown in Figure 1. The times at which each station was sampled are presented in Table II.

Table II

Times at Which River Stations Were Sampled

Station	Time of Sampling (a.m. and p.m.)		
0	12:15	4:15	8:15
1	12:45	4:45	8:45
2	1:00	5:00	9:00
3	1:15	5:15	9:15
4	1:35	5:35	9:35
5	1:55	5:55	9:55
6	2:10	6:10	10:10
7	2:25	6:25	10:25
8	2:45	6:45	10:45

At each station one sample was taken at midchannel from a depth of 12 feet; all measurements except MF coliforms were made on this sample.

Sampling began at midnight on August 5 and 6 and continued until midnight August 29 and 30. The samplers were directed to take each sample as close to the scheduled time as possible. An allowance of ± 5 minutes was permitted if the tide was running and ± 10 minutes at slack tide. If the samples could not be taken within this period, they were not to be taken at all. During the survey, 23 samples were missed out of the 1,305 scheduled. Two of these were due to debris on the river; the remainder were due to motor failure. In addition to these, large numbers of MF coliform counts and algae counts were missed.

Since the time series must be unbroken for much of the statistical analysis, it was necessary to interpolate the missing points. This was done by linear interpolation between observed points. The missed samples are listed in Table III. It is not felt that the small degree of interpolation required has affected the results to any noticeable extent. There were too many missing points in the algae and MF coliform data to permit their reliable use in this type of analysis. The algae counts for Stations 7 and 8 were salvaged to some extent by interpolating 14 and 16 points, respectively. The points interpolated are:

Table III

Samples Not Collected in Time Series

Stations	Sample Numbers Missed	Total Missed
0	65	1
1	18, 49, 59, 63, 65	5
2	45, 65	2
3	45, 58, 59, 70	4
4	45, 58	2
5	45, 58	2
6	45	1
7	45, 54	2
8	18, 45, 54, 113	4

Station 7 - 19, 22, 25, 28, 31, 45, 47, 54, 63, 66, 70, 73, 90, 93;

Station 8 - 2, 18, 19, 45, 47, 54, 56, 61, 65, 66, 73, 90, 93, 105, 113, 125.

ADDITIONAL TIME SERIES DATA

The river station data were augmented by additional data from other agencies in the region. Daily charts of volumes of waste discharged were obtained from the Blue Plains waste treatment plant of the District of Columbia, and from the waste treatment plants of the Pentagon, Arlington, and Alexandria. Daily composite BOD's were obtained from the Blue Plains plant and the results of BOD samples obtained on normal working days were obtained from the other plants. From these data the daily waste loads discharged by each plant were calculated. Where the BOD for a day was not known, the mean BOD for the waste from that plant was used. The results are presented in Table IV. The Pentagon load was such a small fraction of the total that it is not included.

River discharges are measured at Little Falls, a short distance above the head of the estuary. Tidal heights are measured at four locations within the area studied, as shown in Figure 1. Records are made on continuous recording charts. From copies of the pertinent charts provided by the U. S. Geological Survey, hourly and 4-hourly values of river discharge and tidal height were tabulated for analaysis.

Weather data obtained by the Weather Bureau at Washington National Airport were abstracted from the monthly summary sheets and the supplements as routinely published by that agency. Solar intensity measurements from Eppley pyrheliometer readings at a station 2 miles east of Alexandria were also supplied by the Weather Bureau. Hourly and 4-hourly values of all parameters were tabulated for analysis.

Table IV

Daily Waste Loads Discharged to the Potomac Estuary at Washington, D. C.
August 1959

Date	Lbs/Day of BOD_5 Discharged			
	Blue Plains	Alexandria	Arlington	Total
1	36,100	2,040	18,300	56,400
2	34,100	2,510	19,800	56,400
3	58,200	2,680	25,600	86,500
4	61,600	1,850	21,000	84,400
5	69,800	2,370	22,500	94,700
6	86,500	2,690	17,900*	107,100
7	55,400	2,070	15,800	73,300
8	50,000	3,090	24,500*	77,600
9	38,200	2,800	14,900	55,900
10	52,700	2,520	13,700	68,900
11	66,200	2,000	17,300	85,500
12	78,100	1,850	23,200	103,200
13	70,200	1,720	28,200	100,100
14	85,500	1,360	20,600*	107,500
15	62,600	2,460	21,600	86,700
16	64,100	2,460	16,100	82,700
17	70,000	2,810	20,600	93,400
18	52,900	2,430	19,800*	75,100
19	54,900	2,810	25,000	82,700
20	51,200	1,840	20,100	73,100
21	77,300	3,040	20,500*	100,800
22	61,100	2,120	15,900	79,100
23	65,100	2,470	17,200*	84,800
24	69,100	2,690	19,800*	91,600
25	82,400	2,100	15,800	100,300
26	79,400	2,730	24,100	106,200
27	81,200	3,260	26,300	110,800
28	68,500	1,890	17,200*	87,600
29	73,600	3,630	17,600	94,800
Mean	64,000	2,420	20,030	86,450
Percent of Total	74.0	2.8	23.2	100

* Estimated

PRESENTATION OF DATA

The time series of temperature, D.O., and BOD_5 resulting from the river station sampling are presented in Figures 3 through 11. The time series of river discharge, sunlight intensity, and waste discharge from the Blue Plains treatment plant are presented in Figure 12. The tidal height records exhibited a simple sinusoidal variation of semidiurnal period and are not presented here. The time series of data not explicitly used in this report are not presented.

The mean values of measurements at each river station are presented in Table V. The daily mean values of temperature, D.O., and BOD_5 are presented in Tables VI, VII, and VIII. Daily mean values of river discharges are presented in Table IX.

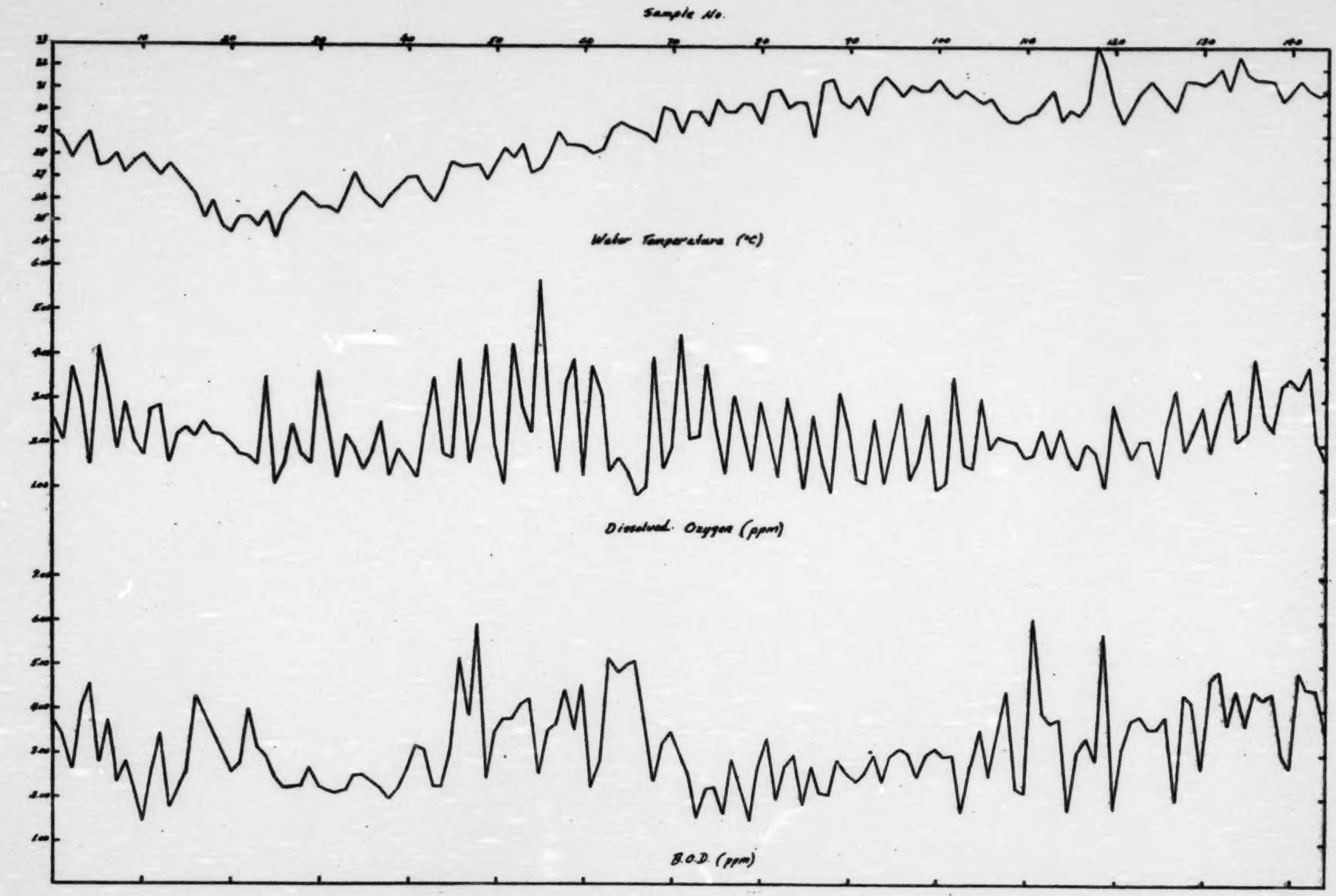


Figure 3. Times Series of D.O., BOD, and Temperature at Station 0

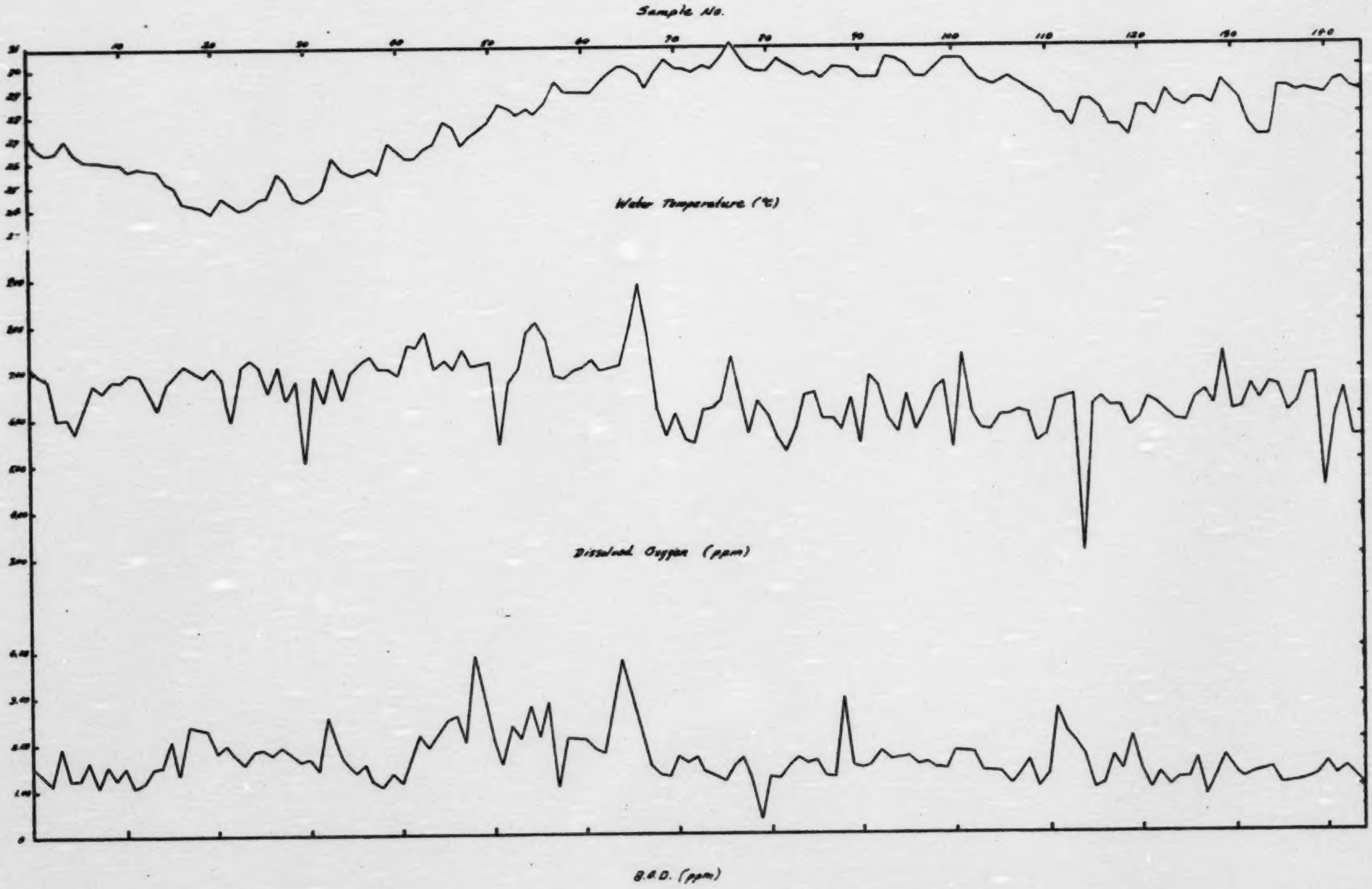


Figure 4. Times Series of D.O., BOD, and Temperature at Station 1

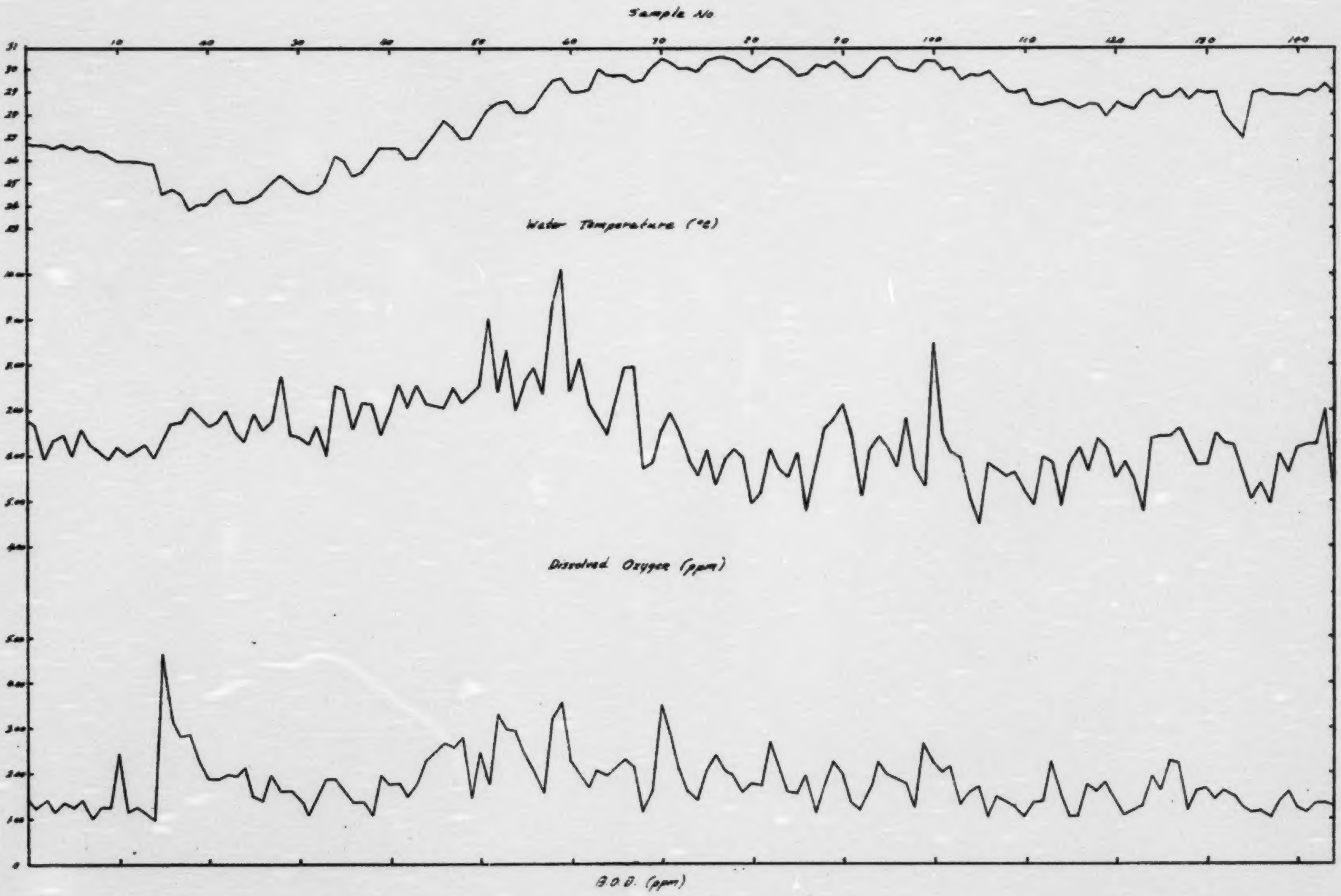


Figure 5. Times Series of D.O., BOD, and Temperature at Station 2

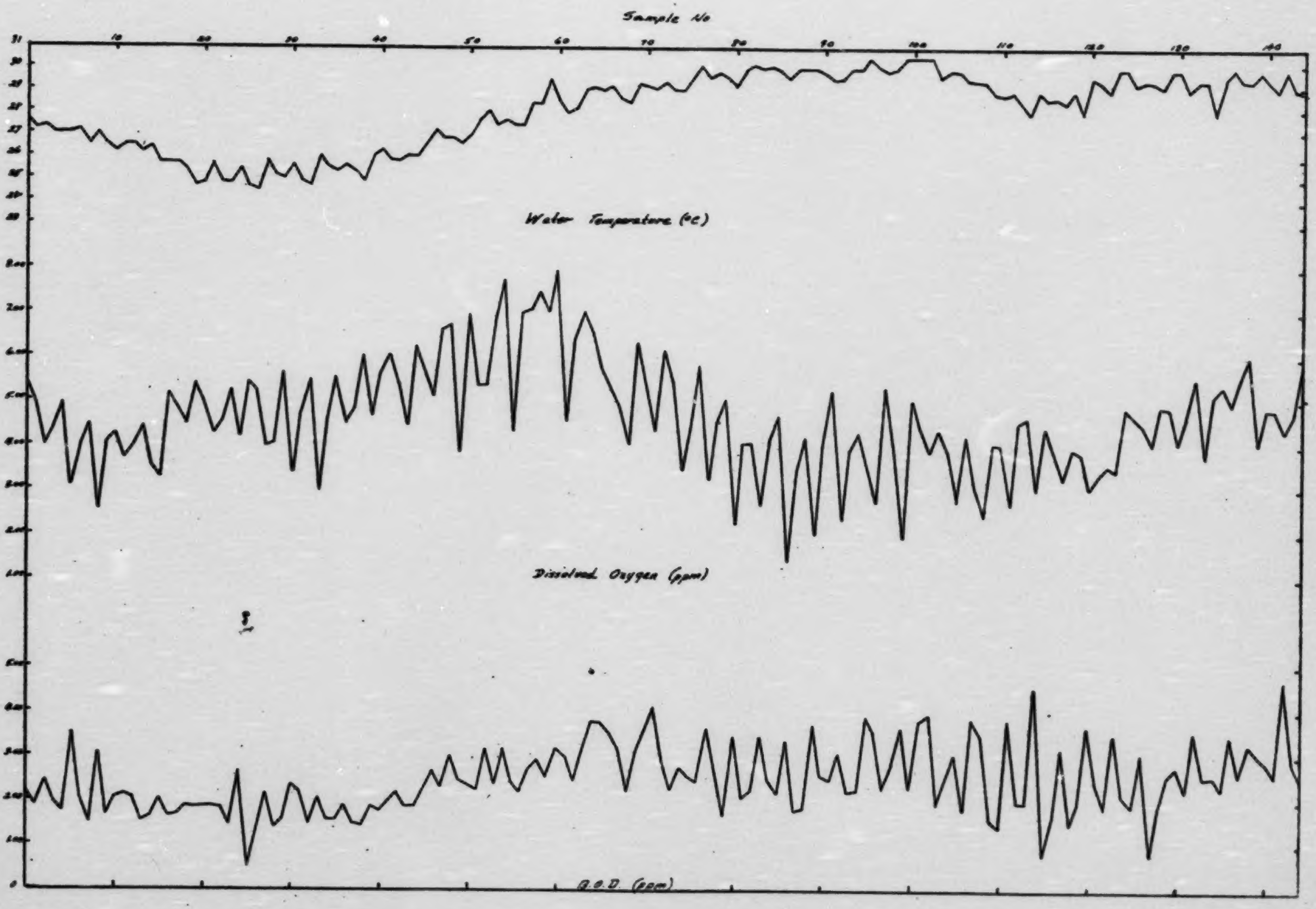


Figure 6. Times Series of D.O., BOD, and Temperature at Station 3

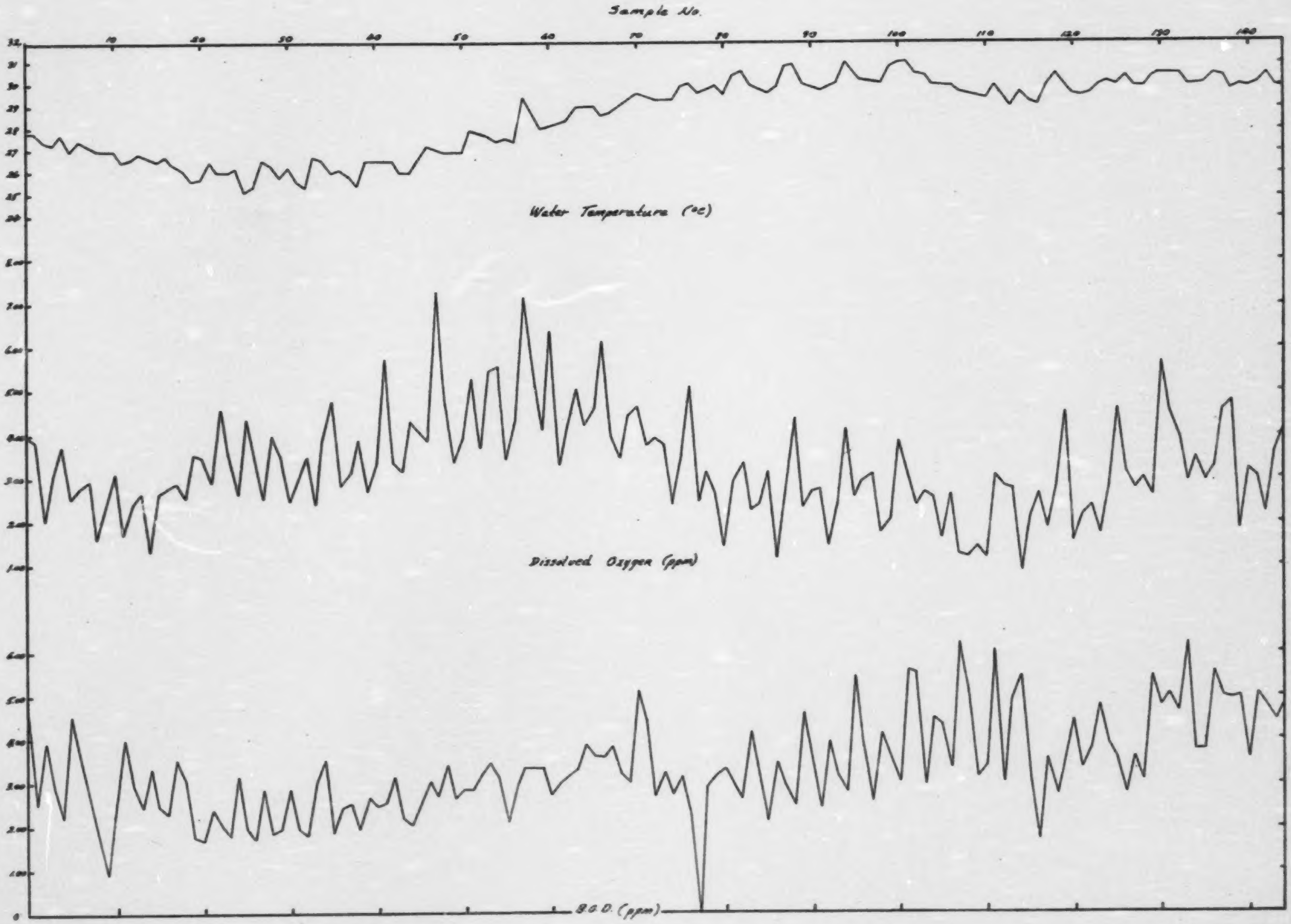


Figure 7a Times Series of D.O., BOD, and Temperature at Station 4

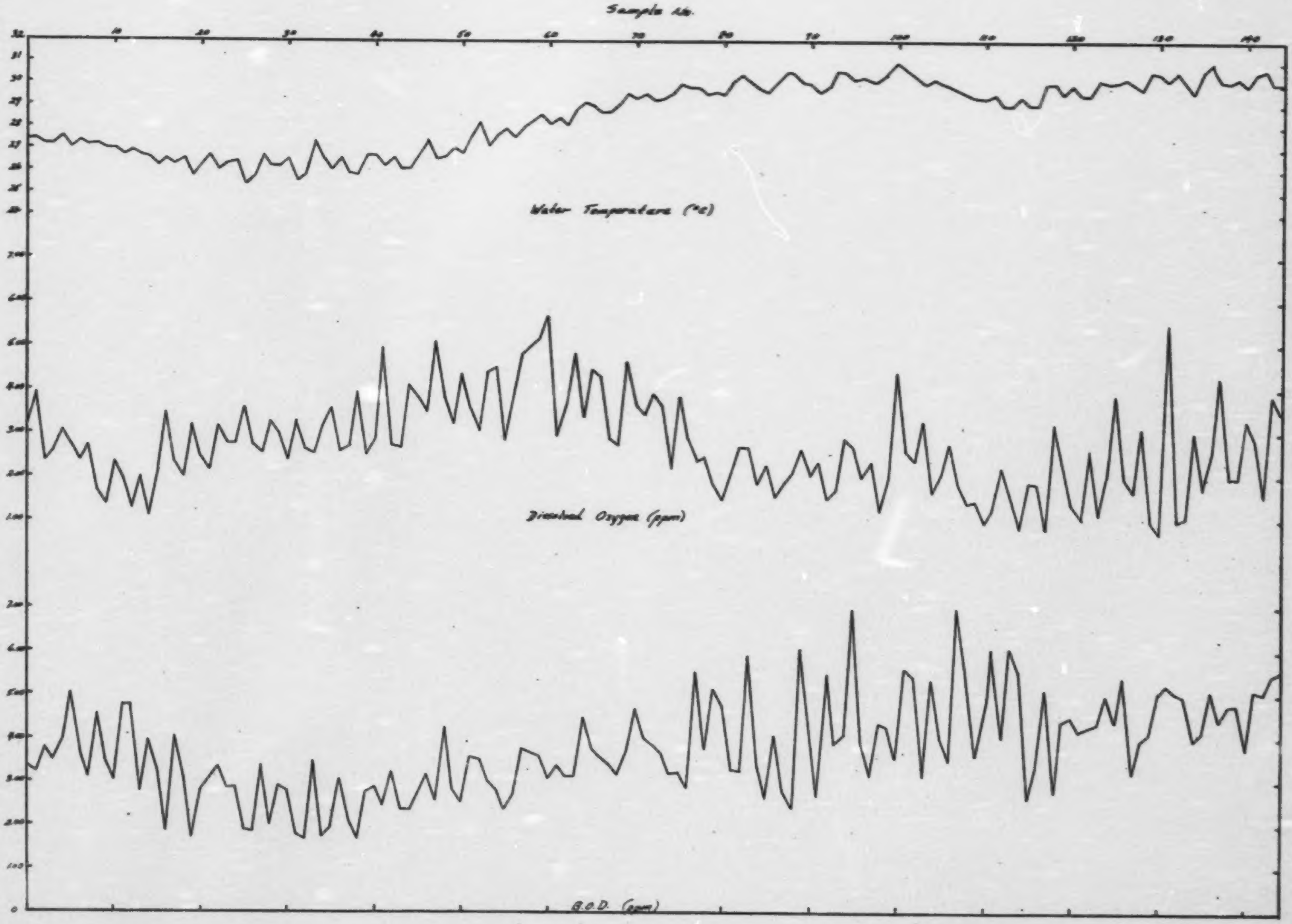


Figure 8. Times Series of D.O., BOD, and Temperature at Station 5

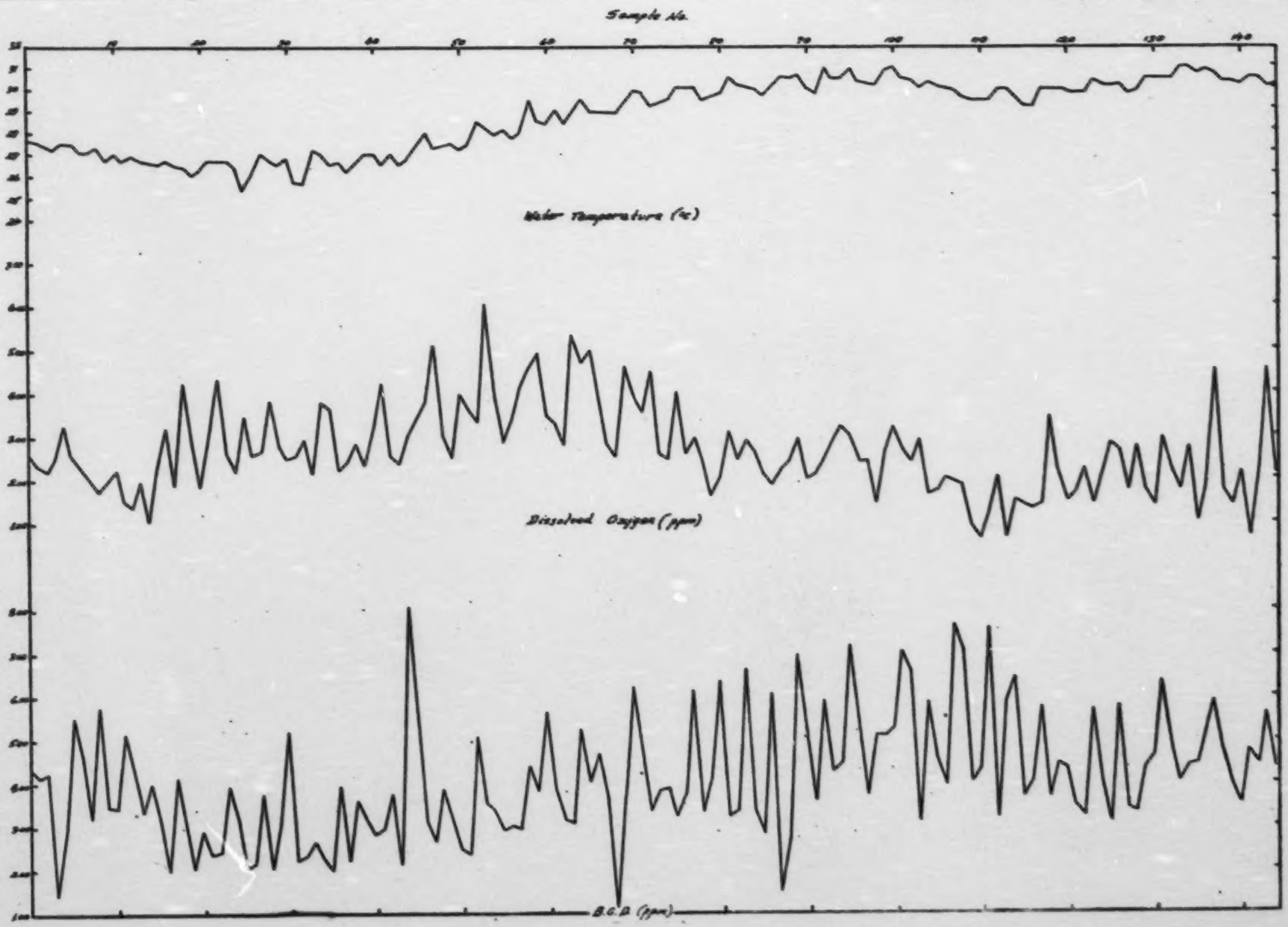


Figure 9. Times Series of D.O., BOD, and Temperature at Station 6

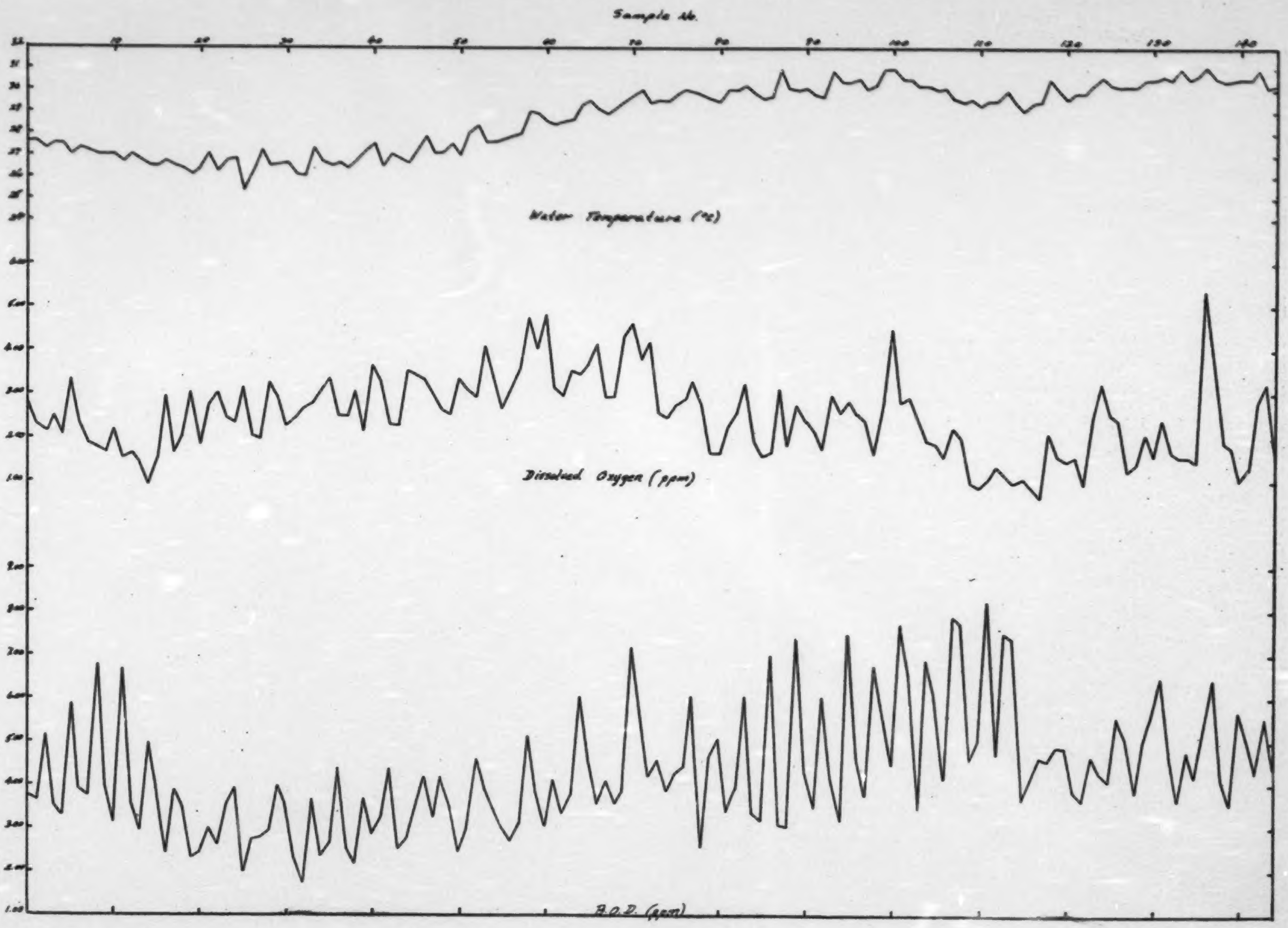


Figure 10. Times Series of D.O., BOD, and Temperature at Station 7.

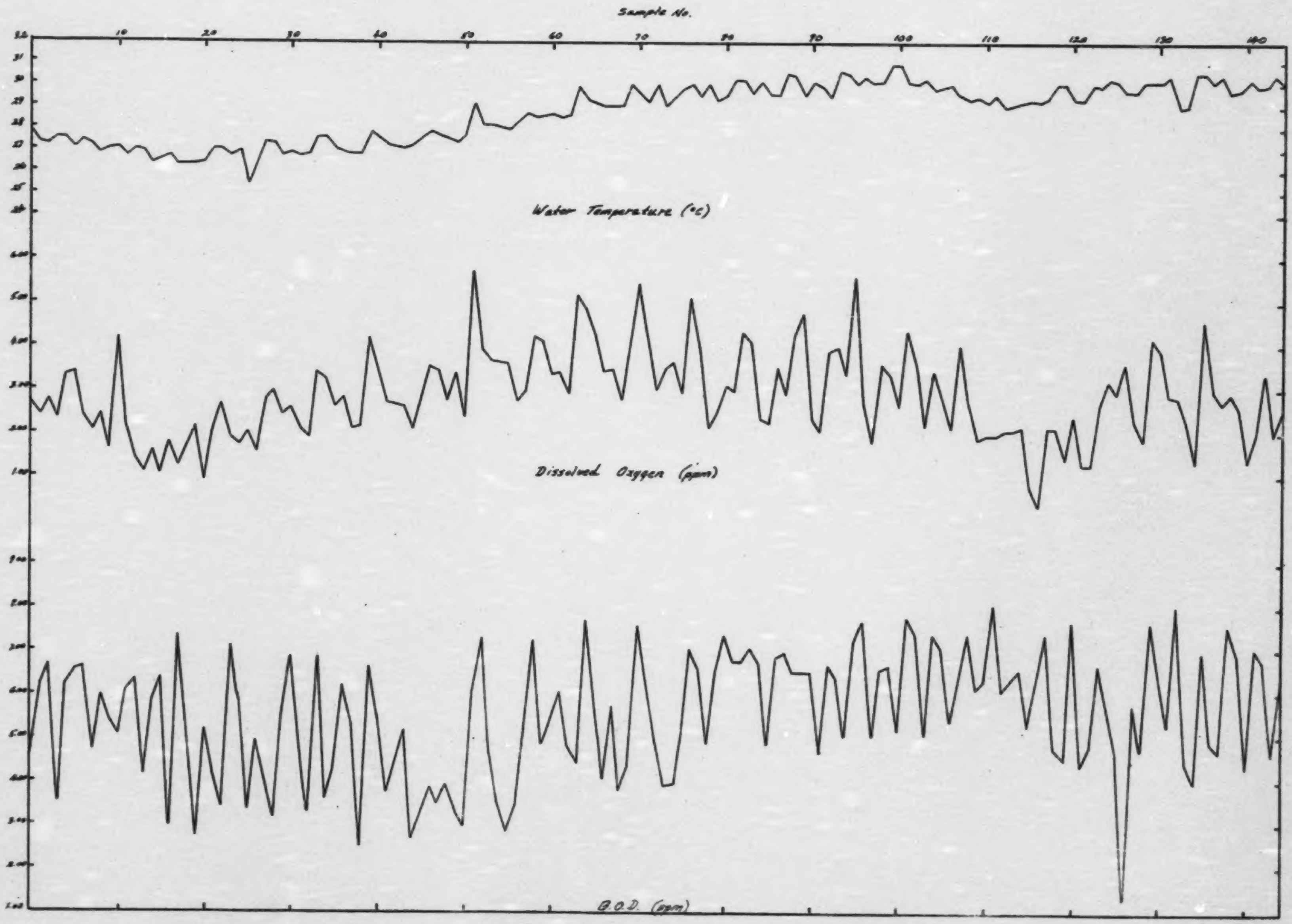


Figure 11. Times Series of D.O., BOD, and Temperature at Station 8

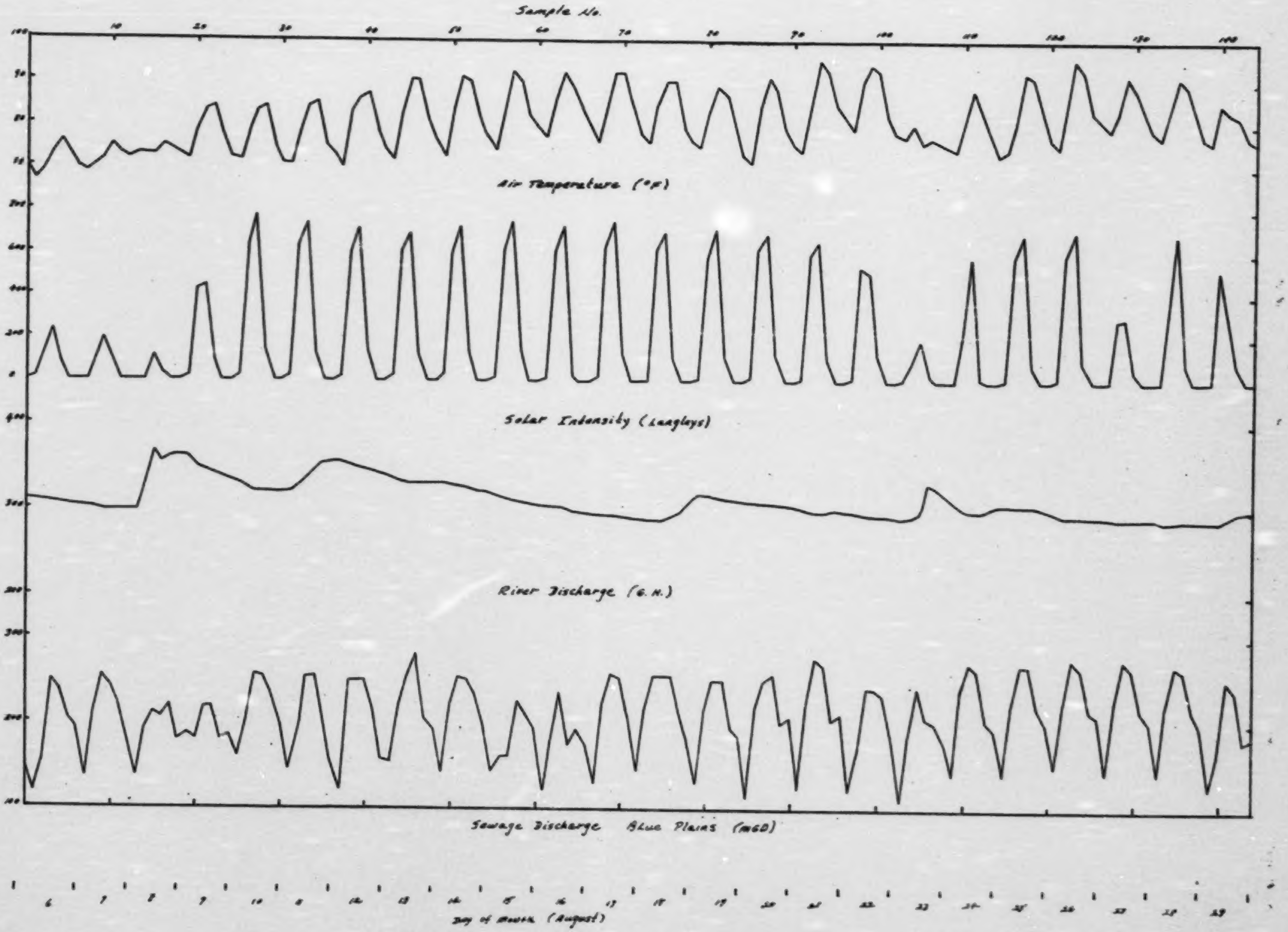


Figure 12. Times Series of Area Parameters

Table V

Mean Values of River Station Data
Potomac Estuary, August 1959

Station	0	1	2	3	4	5	6	7	8
Parameter Measured									
Temp.(^{o}C)	29.0	28.0	28.1	28.1	28.6	28.5	28.8	28.8	28.7
D.O.(ppm)	2.29	6.52	6.36	4.60	3.29	2.70	2.68	2.53	2.83
BOD_5(ppm)	3.15	1.62	1.79	2.44	3.34	3.73	4.10	4.30	5.51
Phosphate(ppm)	0.69	0.24	0.26	0.49	0.90	1.07	1.19	1.18	1.10
Solids(ppm):									
Diss. Vol.	27	25	25	27	27	28	28	27	30
Diss. Fixed	174	168	173	171	171	173	175	175	174
Diss. Total	200	192	198	200	197	201	203	203	204
Sus. Vol.	9.2	7.5	7.9	7.7	7.7	7.6	7.9	7.9	7.9
Sus. Fixed	51	22	25	23	20	20	18	18	18
Sus. Total	60	30	33	31	28	27	27	26	26
Total Vol.	36	33	33	35	35	36	36	35	38
Total Fixed	224	190	198	196	191	194	194	193	192
Total Solids	260	223	231	231	226	229	229	228	231
Turbidity	102	46	48	47	46	43	40	38	36
Algae (per 100 ml.)									
Total Green								12900	11100
Total Diatoms								4110	4530
Total Blue-Green								8920	20200

Temp., D.O., BOD, values based on 145 samples each minus the number missed at each station. The other values are based on 126 samples each minus the number missed. See Table III.

Table VI

Daily Mean Values of Temperature at River Stations
Potomac Estuary, August 1959

Station Date	0	1	2	3	4	5	6	7	8
6	28.2	26.6	26.6	27.1	27.4	27.3	27.4	27.4	27.3
7	27.6	26.0	26.2	26.5	26.9	27.0	27.0	27.0	27.0
8	26.5	25.0	24.9	25.8	26.5	26.5	26.6	26.6	26.5
9	25.0	24.2	24.3	25.0	26.0	26.2	26.5	26.6	26.7
10	25.6	24.7	24.8	25.1	25.9	26.1	26.4	26.4	26.6
11	26.1	25.4	25.3	25.3	26.0	26.3	26.4	26.5	27.1
12	26.4	26.2	26.2	25.7	26.2	26.3	26.7	26.9	27.2
13	27.1	27.1	27.0	26.6	26.6	26.6	27.2	27.1	27.4
14	27.7	28.0	28.0	27.4	27.4	27.4	27.8	27.7	28.0
15	28.3	28.8	28.9	28.3	28.2	28.1	28.4	28.3	28.4
16	28.9	29.7	29.5	28.8	28.7	28.7	29.0	28.9	29.1
17	29.5	29.9	30.0	29.0	29.2	29.2	29.4	29.5	29.5
18	30.1	30.4	30.3	29.5	29.7	29.6	29.8	29.8	29.6
19	30.4	30.0	30.2	29.8	30.0	29.9	30.0	29.9	29.8
20	30.5	29.8	30.0	29.9	30.2	30.1	30.2	30.1	29.9
21	30.9	30.0	30.1	30.0	30.3	30.2	30.5	30.3	30.1
22	31.1	30.2	30.1	30.3	30.6	30.5	30.5	30.6	30.4
23	30.4	29.4	29.6	29.6	30.0	29.9	30.0	29.9	29.8
24	30.1	28.3	28.6	28.7	29.5	29.3	29.7	29.6	29.2
25	31.0	27.9	28.4	28.7	29.8	29.6	29.7	29.7	29.6
26	30.6	28.4	28.7	29.5	29.9	29.9	30.1	30.2	29.9
27	31.3	28.6	28.8	29.5	30.3	30.2	30.3	30.4	29.9
28	31.6	28.4	28.4	29.4	30.1	30.2	30.8	30.7	30.0
29	30.9	29.1	29.1	29.4	30.1	30.2	30.3	30.4	30.0

All values in degrees centigrade.

Table VII

Daily Mean Values of Dissolved Oxygen at River Stations
Potomac Estuary, August 1959

Station	0	1	2	3	4	5	6	7	8
Date									
6	2.95	6.30	6.33	4.22	3.00	2.82	2.56	2.46	2.77
7	2.45	6.82	6.11	3.84	2.37	1.87	1.82	1.78	2.31
8	2.16	6.78	6.52	4.29	2.49	2.16	2.45	1.76	1.42
9	2.11	6.88	6.68	4.77	3.45	2.73	2.81	2.58	1.90
10	1.99	6.52	6.82	4.62	3.41	2.91	2.97	2.62	2.40
11	1.81	6.83	6.76	4.66	3.42	2.94	2.88	2.63	2.68
12	2.36	7.25	7.05	5.42	3.70	3.27	2.92	2.82	2.85
13	2.48	7.30	7.25	5.79	4.57	3.82	3.46	3.30	2.87
14	2.77	6.92	7.78	5.99	4.57	3.83	3.92	3.24	3.77
15	3.05	7.27	8.29	6.79	5.18	4.56	3.89	3.92	3.49
16	2.04	7.53	7.28	5.92	4.60	3.91	4.19	4.17	3.99
17	2.50	6.11	6.59	5.18	4.05	3.52	3.68	3.80	3.83
18	2.51	6.33	5.84	4.50	3.41	2.88	2.85	2.80	3.52
19	2.15	5.90	5.57	3.70	2.52	2.08	2.48	2.22	3.21
20	1.95	6.00	6.19	3.31	2.72	2.05	2.30	2.22	3.33
21	1.82	6.23	5.99	3.69	2.72	2.17	2.72	2.47	3.59
22	1.85	6.36	6.49	4.04	2.73	2.46	2.50	2.84	3.22
23	2.04	5.94	5.44	3.44	1.99	2.12	2.06	1.99	2.87
24	1.99	5.55	5.44	3.82	2.03	1.33	1.20	1.06	1.99
25	1.83	6.12	5.98	3.73	2.61	1.85	1.90	1.30	1.50
26	1.98	6.13	5.90	4.06	2.79	2.09	2.17	2.22	2.44
27	2.46	6.50	6.20	4.68	3.76	2.12	2.17	1.74	2.96
28	2.75	6.46	5.52	5.14	3.65	2.39	2.28	2.52	2.78
29	2.94	5.79	6.14	4.79	3.02	2.79	2.20	1.95	2.28

Table VIII

Daily Mean Values of Biochemical Oxygen Demand at River Stations
Potomac Estuary, August 1959

Station	0	1	2	3	4	5	6	7	8
Date									
6	3.55	1.43	1.31	2.27	3.31	3.88	3.81	4.23	6.01
7	2.49	1.26	1.38	2.08	2.43	3.97	4.22	4.63	5.61
8	3.02	1.84	2.59	1.72	2.87	3.16	3.93	3.59	5.30
9	3.14	1.86	1.99	1.90	2.14	2.77	2.81	2.96	4.73
10	2.32	1.75	1.57	1.54	2.22	2.45	3.04	2.98	4.62
11	2.28	1.72	1.55	1.77	2.46	2.27	2.56	2.84	4.81
12	2.53	1.41	1.56	1.76	2.57	2.50	3.08	3.14	4.68
13	3.77	2.51	2.41	2.31	2.67	2.89	4.27	3.39	3.69
14	3.62	2.30	2.46	2.60	3.04	3.02	3.33	3.48	4.60
15	3.71	2.04	2.50	2.64	2.99	3.17	3.79	3.46	4.83
16	4.21	2.59	2.02	3.27	3.44	3.57	4.02	4.23	5.52
17	3.05	1.50	2.21	3.16	3.73	3.81	3.85	4.75	5.46
18	2.12	1.32	1.89	2.67	2.40	3.70	4.04	4.28	5.22
19	2.52	1.22	1.91	2.56	3.26	4.28	4.53	4.40	6.87
20	2.35	1.65	1.77	2.55	3.23	3.62	4.17	4.64	6.34
21	2.72	1.60	1.70	2.89	3.63	4.49	5.15	4.80	6.26
22	2.88	1.57	2.02	3.10	4.09	4.36	5.47	5.79	6.44
23	3.08	1.30	1.41	2.76	4.41	4.73	5.39	6.01	6.45
24	3.64	1.79	1.47	2.54	4.35	4.94	5.25	6.24	6.57
25	3.08	1.41	1.44	1.92	3.21	3.74	4.35	4.45	5.98
26	3.62	1.19	1.56	2.41	3.71	4.54	4.25	4.33	4.60
27	3.79	1.22	1.62	2.27	4.45	4.37	4.48	5.11	6.32
28	4.13	1.16	1.25	2.77	4.88	4.49	4.79	4.76	5.40
29	3.85	1.24	1.34	3.10	4.60	4.88	4.46	4.75	5.96

Table IX

Daily Mean Values of the Potomac River Discharge at Washington, D. C., August 1959 (cubic feet per second)

Date	Discharge	Date	Discharge	Date	Discharge
1	2000	11	3180	21	1580
2	2320	12	3560	22	1410
3	2400	13	2860	23	1950
4	2320	14	2620	24	1680
5	2130	15	2020	25	1780
6	1860	16	1600	26	1360
7	1570	17	1310	27	1240
8	3430	18	1380	28	1180
9	3430	19	2180	29	1390
10	2490	20	1880		

ANALYSIS OF DATA

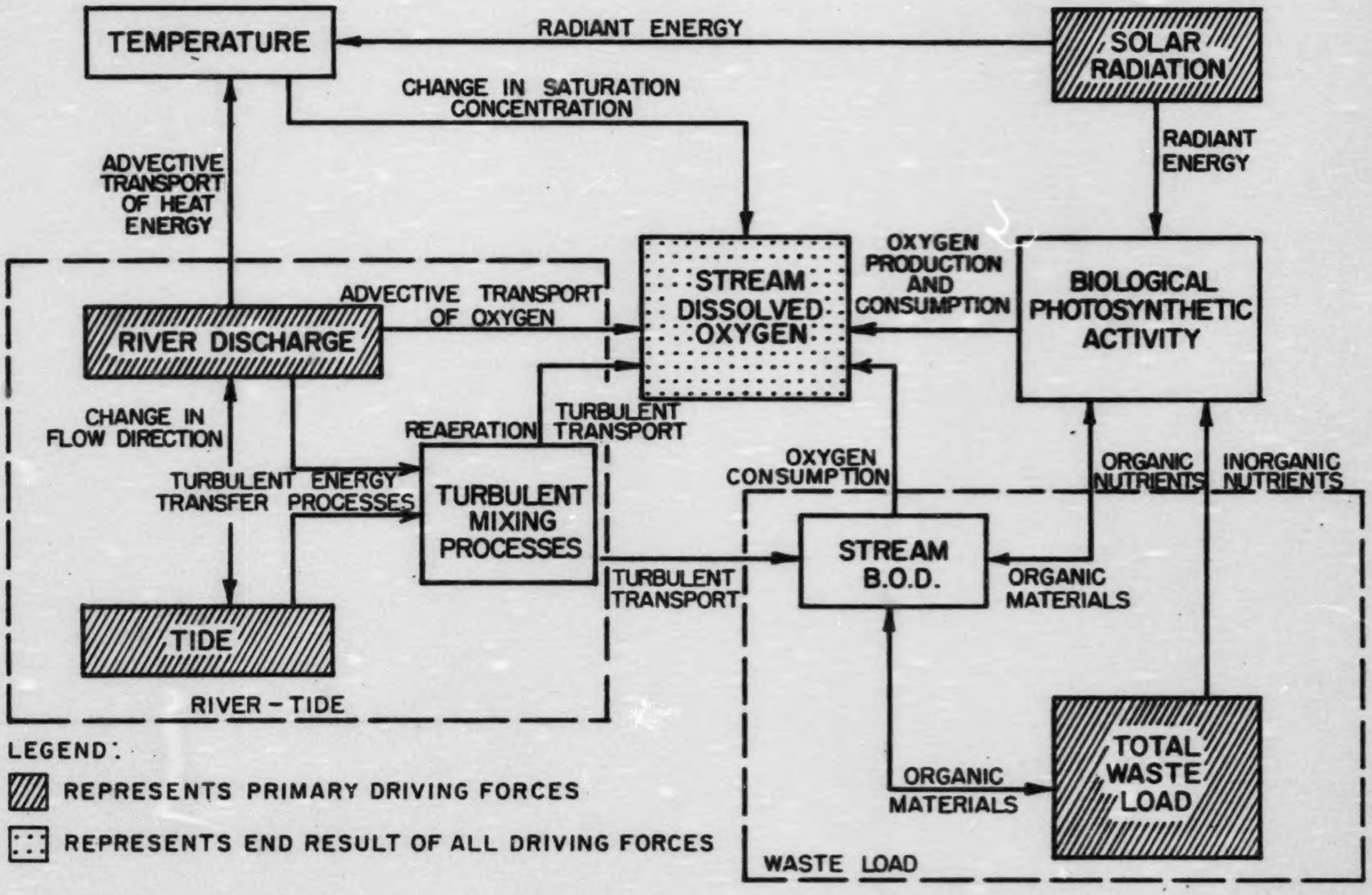
GENERAL APPROACH

The parameter by which the waste assimilation capacity is measured in the stream is the dissolved oxygen concentration which exists in the stream while it is receiving an organic waste load. The observed dissolved oxygen concentration is the result of the interplay of many driving forces. Figure 13 is a schematic representation of the major driving forces which are postulated to affect the stream D.O. in this particular system. This representation is merely a pictorial summary of individual effects which have been postulated and studied for a number of years. Work cited in these references provides ample justification for the relationships shown in this figure:

1. G. M. Fair and J. G. Geyer, Water Supply and Waste-Water Disposal, 973 p. New York, John Wiley and Sons, Inc., 1954. (Particularly Chapters 19 and 28.)

2. H. W. Harvey, The Chemistry and Fertility of Sea Waters. 2nd edition, 234 p. Cambridge, University of Cambridge Press, 1957. (Particularly Capters II through VI.)

3. C. H. J. Hull, "Oxygen Balance of an Estuary." Proceedings of the American Society of Civil Engineers, vol. 86, No. SA6, November 1960.


TEMPERATURE
RADIANT ENERGY
SOLAR RADIATION
CHANGE IN SATURATION CONCENTRATION
RADIANT ENERGY
ADVECTIVE TRANSPORT OF HEAT ENERGY
OXYGEN PRODUCTION AND CONSUMPTION
STREAM DISSOLVED OXYGEN
BIOLOGICAL PHOTOSYNTHETIC ACTIVITY
ADVECTIVE TRANSPORT OF OXYGEN
RIVER DISCHARGE
CHANGE IN FLOW DIRECTION
REAERATION
TURBULENT TRANSPORT
TURBULENT ENERGY TRANSFER PROCESSES
TURBULENT MIXING PROCESSES
OXYGEN CONSUMPTION
ORGANIC NUTRIENTS
INORGANIC NUTRIENTS
STREAM B.O.D.
ORGANIC MATERIALS
TURBULENT TRANSPORT
TIDE
RIVER – TIDE
ORGANIC MATERIALS
TOTAL WASTE LOAD
WASTE LOAD
LEGEND:
REPRESENTS PRIMARY DRIVING FORCES
REPRESENTS END RESULT OF ALL DRIVING FORCES

FACTORS AFFECTING STREAM DISSOLVED OXYGEN CONCENTRATION

FIGURE 13

While the internal workings of this system are quite complex, it can be seen from this figure that the observed stream D.O. is controlled by the operation of four primary driving forces. These are:

1. Solar radiation.
2. Total waste load.
3. River discharge.
4. Tide.

The methods by which these primary forces act on the system differ in character as well as in magnitude. Solar radiation has two primary effects. First, it exerts a partial controlling influence on the direct production and consumption of oxygen by the aquatic biota. Second, its presence or absence changes the temperature of the water, thereby controlling the quantity of oxygen the water can dissolve. The total waste load also has two major indirect effects. First, it supplies inorganic and organic nutrients to the biota. Second, it supplies inert organic materials which are decomposed with the consumption of oxygen. The effects of the total waste load are measured in the stream as the biochemical oxygen demand (BOD) whether the source of the waste load is an untreated sewage, a treatment plant effluent, sludge beds, storm water overflows, or natural drainage. When using the BOD determination on stream samples, it is impossible to differentiate between these sources of pollution without information on the individual sources themselves. The river discharge has three major effects. First, it brings oxygen into the system by advective transport processes. Second, it may partially control the temperature by bringing in a surplus or deficit of thermal energy in comparison with the tidal system itself. Third, it combines with the tide in controlling the turbulent mixing processes of the system and by doing so affects the reaeration capability of the system. The tide itself functions as an energy source for the turbulent mixing processes and thereby aids in controlling the reaeration capability of the stream. The tide and the river discharge act in combination on the system. The parameter measured in this study, which has been called "tide height," is actually a measure of the combined effect of tidal flow and river discharge. It should also be noted that the measurement of "tide height" is not a direct measure of the energy supplied by tidal action; neither is river discharge an adequate measure of the energy supplied from this source. The total energy supply and its use can be measured only indirectly through the observed changes which occur. Since the energy input from tidal action can be regarded as relatively constant, any changes which occur in the turbulence regime from this combined effect can be attributed to changes in the energy supplied by the river discharge.

The possibility of interactions among other combinations of primary drivers should also be considered. It is not likely that either river discharge, tide, or the combination of these is related to either the total waste load or solar radiation. Nor is it likely that solar radiation and the total waste load directly affect each other. It is likely, however, that these two driving forces are related to each other through the biological system and its relationship to stream BOD. Since stream BOD is the major parameter by which total waste load is measured, it is necessary that the effect of sunlight on stream BOD be determined and the results included in the subsequent analyses. It should be noted that it is possible to do this only because it may be assumed that stream BOD does not affect solar radiation. If these two parameters did affect each other, as in the case of tide height and river discharge, then it would be necessary to regard the solar radiation and stream BOD as a single primary driving force.

The general approach used in the analysis of the data obtained in this survey has been to regard the observed D.O. fluctuations in the stream as resulting directly from the effects of the primary driving forces as measured by solar radiation intensity, tidal height-river discharge, and stream BOD. The technique used in the data analysis was chosen because it supplied a procedure for calculating the stream D.O. response to each of these parameters.

It should be noted that, using this technique, the total response of D.O. to sunlight, for example, can be measured directly from the records of sunlight and dissolved oxygen. This does not mean that the effect of temperature, for example, is being ignored. It is a part of the sunlight effect and is included in the stream D.O. response along with algal effects and any other sunlight effects which bring about a change in D.O.

It should be emphasized, however, that the technique used here is purely a statistical method for handling large quantities of time series data which may or may not be afflicted with large quantities of random "noise." It derives its utility from its property of being able to separate the "noise" from the "signal" or "signals." It cannot determine whether or not the "signal" mean anything. For example, the technique will not state whether or not D.O. does respond to solar radiation; it will state that if there is a response of D.O. to solar radiation, this is probably what it is. In short, the technique produces a statistic, the existence of which must be justified on some physical basis.

Specifically, the data obtained in this study were analyzed in three ways:

1. From the spectral analysis results, the D.O. responses to sunlight and stream BOD were added together and subtracted from the observed total D.O. response. The remaining response was then attributed to the effects of the tide-river discharge system.
2. From the spectral analysis results, the effects of tide-river discharge on stream D.O. through temperature, the advective transport of oxygen, and the turbulent regime were calculated without reference to sunlight or stream BOD effects.
3. From long-term BOD's and gross calculations based on daily mean values, the classical oxygen-sag formulation was used to estimate "reaeration rate constants" as functions of river discharge.

TECHNIQUES OF DATA ANALYSIS

One of the most powerful tools presently available in statistical dynamics is spectral analysis. Since it is the principal technique upon which the results presented in this report are based, it is necessary to discuss some aspects of its mechanism and utility.

Spectral analysis consists of splitting the total variance of a record into a number of frequency bands and computing the amount of the variance that can be attributed to each band. This is done by first computing the lagged products of the sequence of values in a record to get the autocorrelation function, then computing the Fourier cosine transform, and finally computing weighted averages to produce a smoothed function which is the final spectral estimate.

By way of illustration, suppose* that there is a record with these values appearing in sequence: 2.00, 1.83, 2.98, 3.57, 1.23, 1.78, 1.56, 1.99, 3.07, 2.77. The zero lagged product and the next three lagged products are obtained in this manner:

lag 0

2.00 x 2.00 = 4.00
1.83 x 1.83 = 3.35
2.98 x 2.98 = 8.88
3.57 x 3.57 = 12.74
1.23 x 1.23 = 1.51
1.78 x 1.78 = 3.17
1.56 x 1.56 = 2.43
1.99 x 1.99 = 3.96
3.07 x 3.07 = 9.42
2.77 x 2.77 = 7.67

Sum = 57.13

lag 1

2.00
1.83 x 2.00 = 3.66
2.98 x 1.83 = 5.45
3.57 x 2.98 = 10.64
1.23 x 3.57 = 4.39
1.78 x 1.23 = 2.19
1.56 x 1.78 = 2.78
1.99 x 1.56 = 3.10
3.07 x 1.99 = 6.11
2.77 x 3.07 = 8.50

Sum = 46.82

lag 2

2.00
1.83
2.98 x 2.00 = 5.96
3.57 x 1.83 = 6.53
1.23 x 2.98 = 3.67
1.78 x 3.57 = 6.35
1.56 x 1.23 = 1.92
1.99 x 1.78 = 3.54
3.07 x 1.56 = 4.79
2.77 x 1.99 = 5.51

Sum = 38.27

lag 3

2.00
1.83
2.98
3.57 x 2.00 = 7.14
1.23 x 1.83 = 2.25
1.78 x 2.98 = 5.30
1.56 x 3.57 = 5.57
1.99 x 1.23 = 2.45
3.07 x 1.78 = 5.46
2.77 x 1.56 = 4.32

Sum = 32.49

The autocorrelation function is the sum of the products for each lag, divided by the number of products. For example:

lag 0 - $\frac{57.13}{10} = 5.71$ = autocorrelation function for lag 0

lag 1 - $\frac{46.82}{9} = 5.20$ = autocorrelation function for lag 1

lag 2 - $\frac{38.27}{8} = 4.78$ = autocorrelation function for lag 2

lag 3 - $\frac{32.49}{7} = 4.64$ = autocorrelation function for lag 3

Autocorrelation functions have a tendency to be somewhat statistically unstable; the Fourier cosin transform of the autocorrelation is somewhat more stable. The autocorrelations are therefore transformed by weighting them with a cosinusoidal function with an amplitude proportional to the autocorrelation and a period proportional to the number of lags being used. This operation, however, causes the spectral estimates to overlap too much, so another weighting function is applied to reduce this effect, and the results are the final spectral estimates. For each lag used, a spectral estimate in one frequency band will be obtained. While it is apparent that the number of estimates obtained are directly proportional to the number of lags used, it should also be noted that the use of each lag involves the loss of one data point and, as a result, there is a consequent loss of stability in the estimates obtained. In any program of spectral analysis, it is necessary that the requirements of precision and resolution be balanced against each other.

There is another effect which must be considered in the use of spectral analysis. The variance estimates are evenly spaced on a frequency interval from zero to the Nyquist or folding frequency. The Nyquist frequency is the highest frequency about which the analysis provides information; it is the reciprocal of twice the sampling interval. However, any "power" present in the record at frequencies above the Nyquist frequency is not simply discarded; it is reported erroneously at frequencies lower than the Nyquist frequency. Thus, in order to get a true concept of the spectrum, the sampling rate must be sufficiently rapid to ensure that the record contains no appreciable power at frequencies higher than the Nyquist frequency. It is therefore useful to have some idea of the dominant frequencies present.

In developing a sampling and data analysis program involving computation of spectra, there are three factors which can be adjusted to obtain the best balance between precision of estimates, resolution of spectral bands, and control of aliasing. These are: (1) sampling interval, (2) total length of record, and (3) number of lags used in computation. For the present study, it was decided to use a sampling interval of 4 hours, a total record length corresponding to 145 samples, and computation to 12 lags. This produces 12 spectral estimates of periods ranging from 8 hours to infinity, each estimate being stable to 23 degrees of freedom. The spectral bands for which estimates are obtained are centered at frequencies corresponding to periods of 8, 8.7, 9.6, 10.7, 12, 13.7, 16, 19.2, 24, 32, 48, and 96 hours, in addition to the zero frequency estimate which includes all long-period effects from the 96-hour period up. It was felt that this balance would provide the best estimates of the 12- and 24-hour effects which were believed to dominate the system.

The computation of cross-spectra is another extremely powerful tool of statistical dynamics. The method of computation is similar to that for the spectral analysis of an individual record. In this case, however, one record is correlated with another record instead of with itself. The cross-correlation functions are computed, Fourier transformed, and smoothed to give the two final cross-spectral estimates corresponding to each lag.* This procedure can also produce: (1) response functions, which show how one record responds to the other; (2) phase shifts, which show how much time is required for changes in one record to be reflected in changes in the other; and (3) coherencies, which show how well linear changes in one record correspond to linear changes in the other.

The frequency response functions are of particular interest in this study. This statistic is computed from the spectral estimates of the individual records and the cross-spectrum of the two records in this manner. Let

$F_A(f)$ = the spectral estimate of record A at the frequency f.

$F_B(f)$ = the spectral estimate of record B at the frequency f.

$[F_B(f)]_A$ = that part of $F_B(f)$ which is due to $F_A(f)$.

$Y_{BA}(f)$ = the response of B to A at frequency f = the frequency response function.

---

*The cospectrum is computed using the Fourier cosine transform on one set of cross-correlation functions.
The quadrature spectrum is computed using the Fourier sine transform on the other set of cross-correlation functions. The final estimates are then 90° out of phase and the actual phase lag can be computed from these components.

$A(f)$ = a function of the cross-spectrum estimates at frequency f.

$c(f)$ = cospectrum at f.
$q(f)$ = quadrature spectrum at f.

$$A(f) = \left| \sqrt{[c(f)]^2 + [q(f)]^2} \right| .$$

Then

$$Y_{BA}(f) = \frac{A(f)}{F_A(f)}$$

and

$$[F_B(f)]_A = \left| Y_{BA}(f) \right|^2 F_A(f).$$

In practice it is simpler to compute $\left[F_B(f) \right]_A$ directly from $A(f)$ in this manner.

$$\left[F_B(f) \right]_A = \frac{[A(f)]^2}{F_A(f)} .$$

Many of the computations outlined here and used in the data analysis are much too laborious and time consuming to carry out by hand. For much of the computation an IBM 704 computer was used; for some of the statistical statics computation an IBM 650 was used. The programs used were developed at New York University, primarily by Mr. Emanuel Mehr; the computation was supervised by Mr. Mehr.

The mathematical basis for the computer programs is contained in these relations:

1. The spectrum program obtains spectra from empirical data by forming the autocorrelation function, R_k, computing the Fourier cosine transform, L_n, and forming weighted averages to get a smoothed function, U_n.

$$R_k = \frac{1}{N-k} \sum_{i=1}^{N-k} x_i x_i + k \qquad k = 0,\ 1,\ 2 \ldots M'$$

$$L_o = \frac{1}{M'} \left[1/2\ (R_o + R_{M'}) + \sum_{k=1}^{M'-1} R_k \right]$$

$$L_n = \frac{2}{M'} \left\{ 1/2\ [R_o + (-1)^n R_{M'}] = \sum_{k=1}^{M'-1} R_k \cos \frac{kn}{M'} \right\}$$

$$n = 1,\ 2,\ 3, \ldots M'-1$$

$$L_{M'} = \frac{1}{M'} \left\{ 1/2\ [R_o + (-1)^{M'} R_{M'}] + \sum_{k=1}^{M'-1} (-1)^k R_k \right\}$$

$$U_n = \sum_{i=o}^{M'} a_{n,i} L_n \qquad n = 1,\ 2,\ 3, \ldots M'-1$$

where:

$a_{n,n-1} = 0.23$

$a_{n,n} = 0.54$

$a_{n,n+1} = 0.23$

$a_{n,i} = 0$ for $i = n-1,\ n,\ n+1$

$N \leq 4{,}000$

$M \leq 400$

$M' \leq M$

2. The cospectrum and quadrature spectrum program obtains cross-spectra from empirical data by forming the cross-correlation functions, S_k^+ and S_k^-, computing the Fourier cosine transform, C_n, for S_k^+ and the Fourier sine transform, Q_n, for S_k^-, and taking weighted averages of C_n and Q_n to get smoothed functions, UC_n and UQ_n. The relations are computed for the paired sequence of data $x_1, x_2, x_3 \ldots x_n$; $y_1, y_2, y_3 \ldots y_n$.

$$S_k^+ = \frac{1}{2(N-k)} \sum_{i=1}^{N-k} (x_i y_{i+k} y_i) \qquad k = 0, 1, 2, \ldots M'$$

$$S_k^- = \frac{1}{2(N-k)} \sum_{i=1}^{N-k} (x_i y_{i+k} - x_{i+k} y_i) \qquad k = 0, 1, 2, \ldots M'$$

$$C_o = \frac{1}{M'} \left[1/2(S_o^+ + S_{M'}^+) + \sum_{k=1}^{M'-1} S_k^+ \right]$$

$$C_n = \frac{2}{M'} \left\{ 1/2\, [S_o^+ + (-1)^n S_{M'}^+] + \sum_{k=1}^{M'-1} S_k \cos \frac{\pi kn}{M'} \right\}$$

$$n = 1, 2, 3, \ldots M'-1$$

$$C_{M'} = \frac{1}{M'} \left\{ 1/2\, [S_o^+ + (-1)^{M'} S_{M'}^+] + \sum_{k=1}^{M'-1} (-1)^k S_k^+ \right\}$$

$$Q_o = 0$$

$$Q_n = \frac{2}{M'} \sum_{k=1}^{M'-1} S_k^- \sin \frac{\pi kn}{M'} \qquad n = 1, 2, 3, \ldots M'-1$$

$$Q_{M'} = 0$$

$$UC_n = \sum_{i=o}^{M'} a_{n,i} C_n \qquad n = 1, 2, 3, \ldots M'-1$$

$$UQ_n = \sum_{i=o}^{M'} a_{n,i} Q_n \qquad n = 1, 2, 3, \ldots M'-1$$

where:

$a_{n,n-1} = 0.23$

$a_{n,n} = 0.54$

$a_{n,n+1} = 0.23$

$a_{n,i} = 0$ for $i \neq n-1, n, n+1$

$N \leq 4{,}000$

$M \leq 400$

$M' \leq M$

Spectra were run on all of the records for which sufficient data were taken. Cross-spectra were run on about 400 selected pairs of records. This presentation of spectral analysis has necessarily been somewhat sketchy and qualitative. It is unfortunate that there is no single reference which covers the many important aspects of this technique. A list of pertinent references is presented here.

1. J. S. Bendat, Principles and Applications of Random Noise Theory, 431 p. New York, John Wiley and Sons, Inc., 1958.

2. R. B. Blackman and J. W. Tukey, The Measurement of Power Spectra, 190 p. New York, Dover Publications, 1958.

3. N. R. Goodman, On the Joint Estimation of the Spectra, Cospectrum and Quadrature Spectrum of a Two-Dimensional Gaussian Process. New York, New York University, 1957. (Scientific Paper No. 10, Engineering Statistics Laboratory.)

4. U. Grenander and M. Rosenblatt, Statistical Analysis of Stationary Time Series, 300 p. New York, John Wiley and Sons, Inc., 1957.

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RESULTS OF DATA ANALYSIS

Individual Power Spectra

The results of spectral analysis of the D.O. records are presented in Figures 14 through 22. The abscissa's are given in terms of arbitrary spectral band numbers for convenience in plotting. The periods corresponding to the band numbers are given in Table X. It should be noted that Band Number 4 corresponds to a diurnal period and that Band Number 8 corresponds to a semidiurnal period. The 90-percent confidence limits are entered on this series of figures only. The confidence limits for the remainder of the spectra are similar.

Table X

Spectral Periods Corresponding to Band Numbers
in Spectral Analysis Graphs

Band Number	Period (hours)
0	00
1	96
2	48
3	32
4	24
5	19.2
6	16
7	13.7
8	12
9	10.7
10	9.6
11	8.7
12	8

There are significant changes in the D.O. spectra from Station 1 at the head of the system to Station 8 which is several miles below the major waste discharge. While all the D.O. records are dominated by long-period effects, the diurnal and semidiurnal effects are also of significant importance. At Station 1 the total variance is comparatively small and there are no significant diurnal or semidiurnal effects. At Station 2 there is a somewhat larger total variance and there are barely significant diurnal and shorter-period effects. Station 3 exhibits a very large total

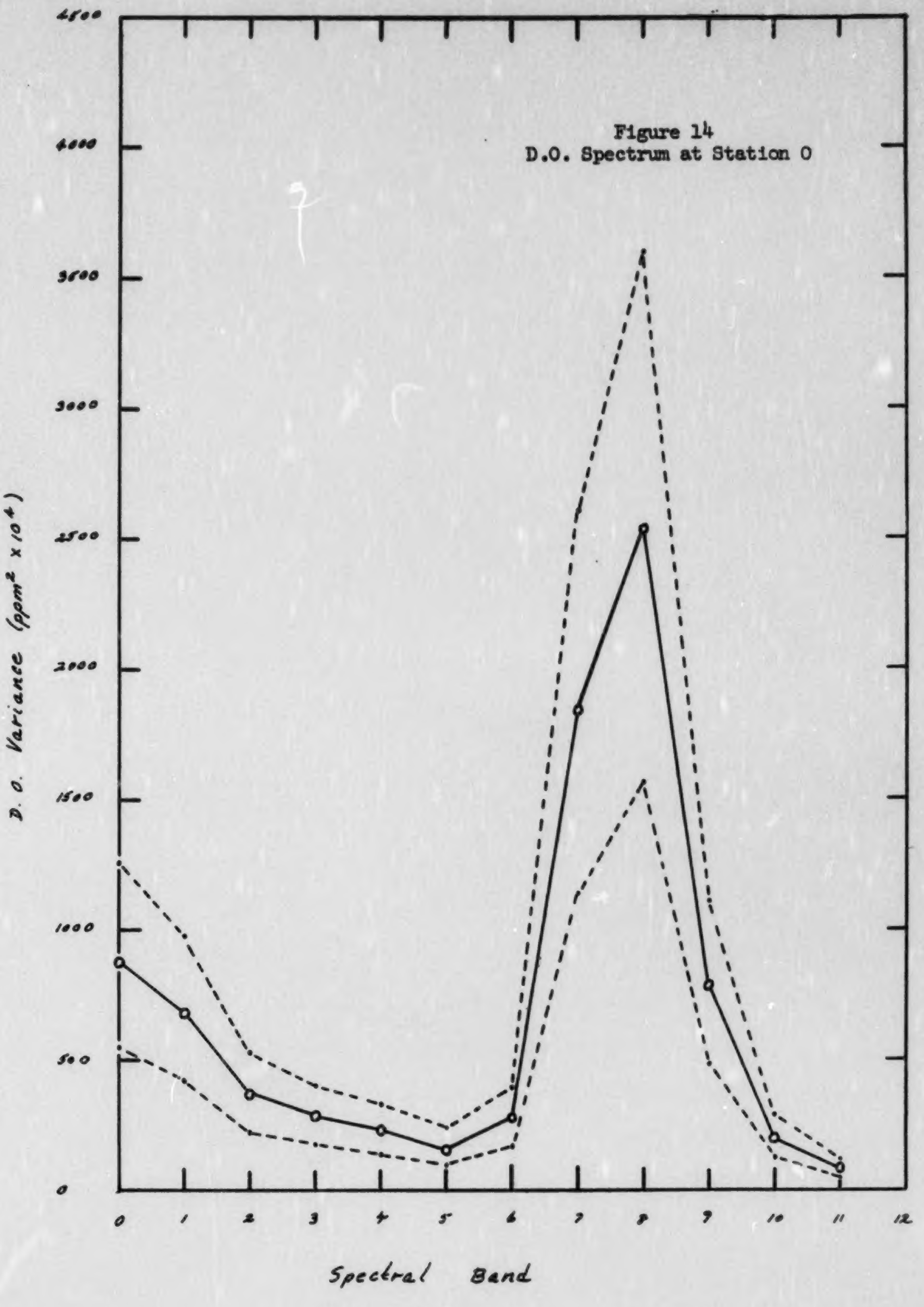


Figure 14
D.O. Spectrum at Station 0

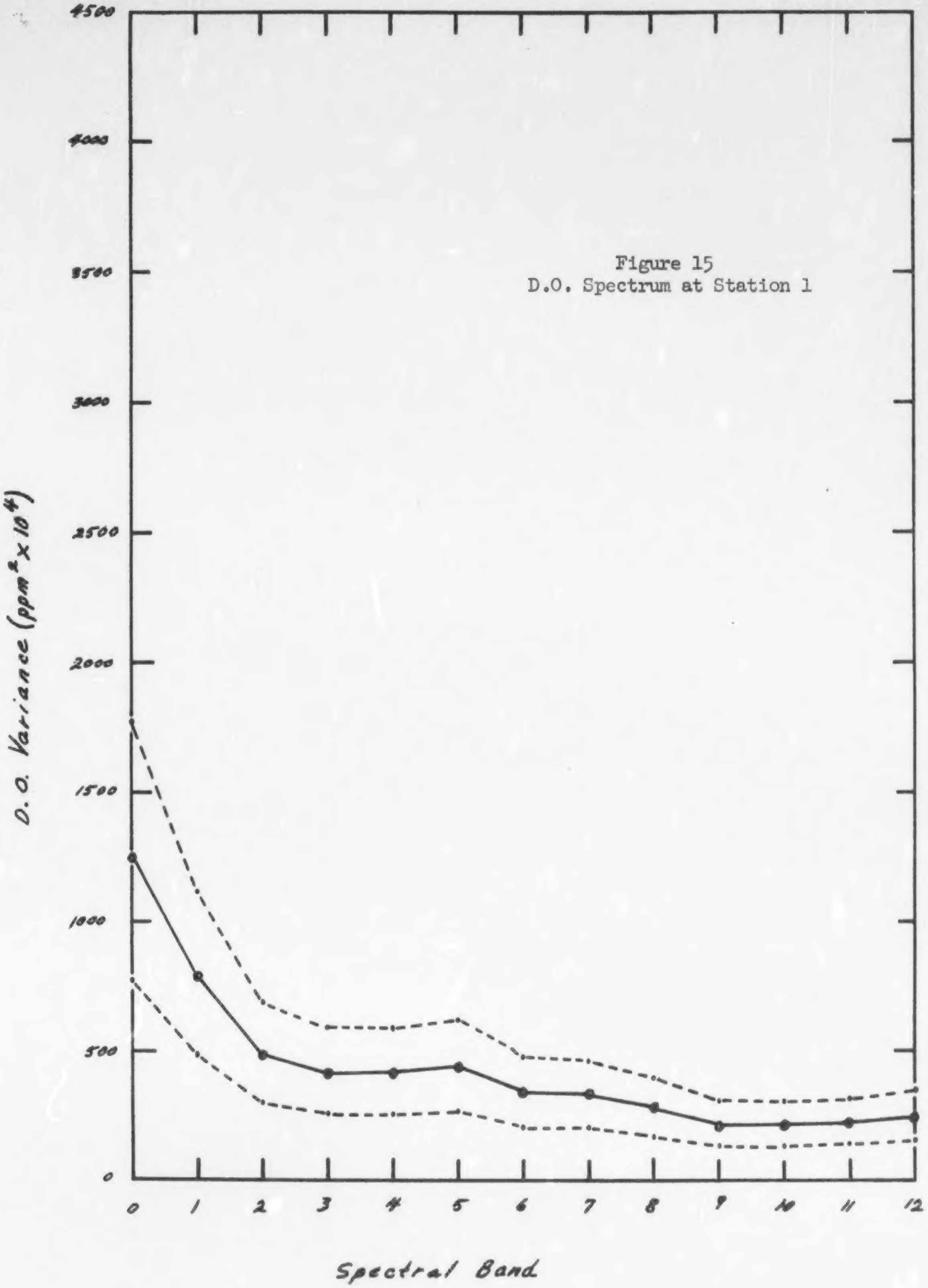


Figure 15
D.O. Spectrum at Station 1

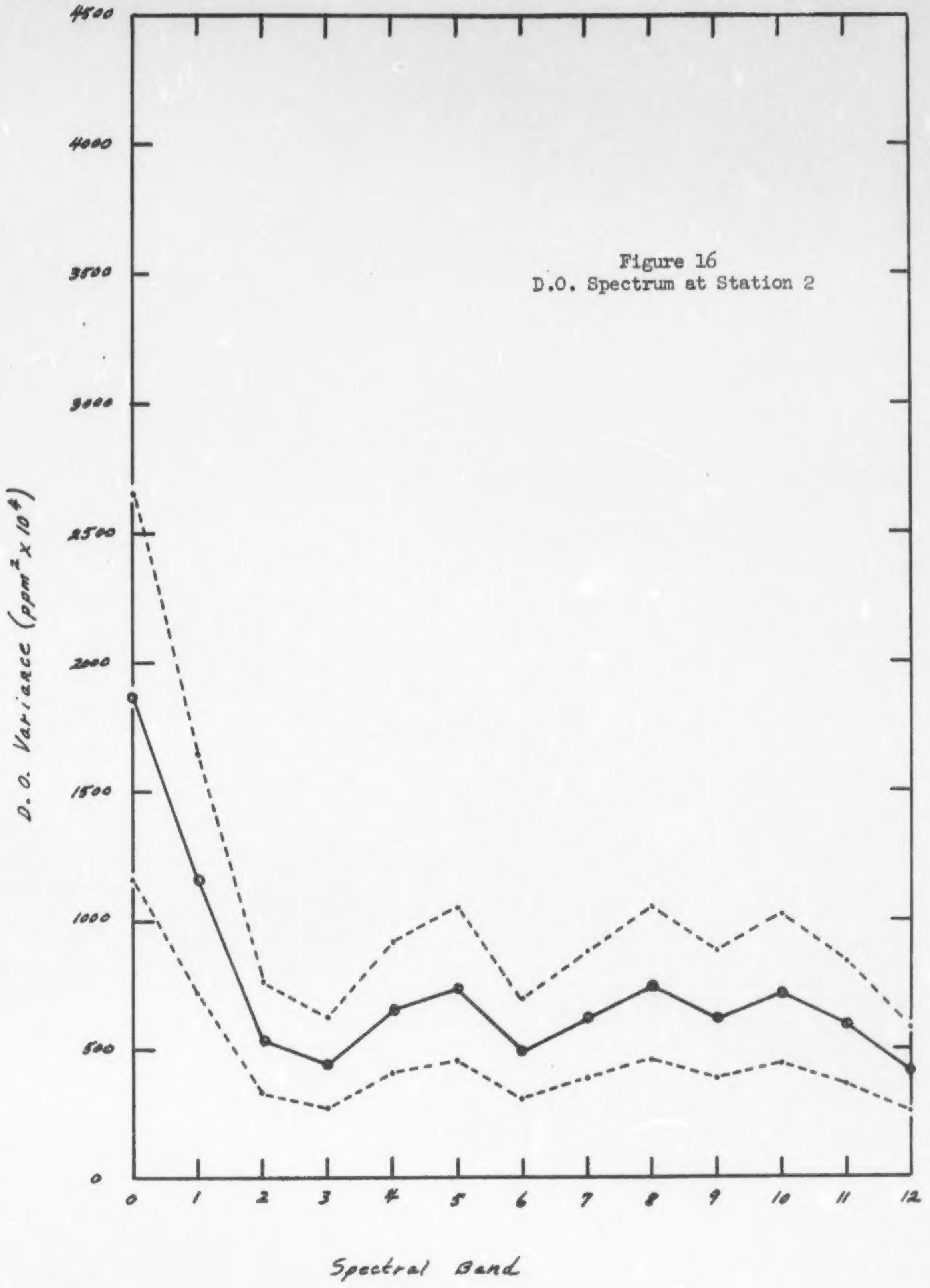


Figure 16
D.O. Spectrum at Station 2

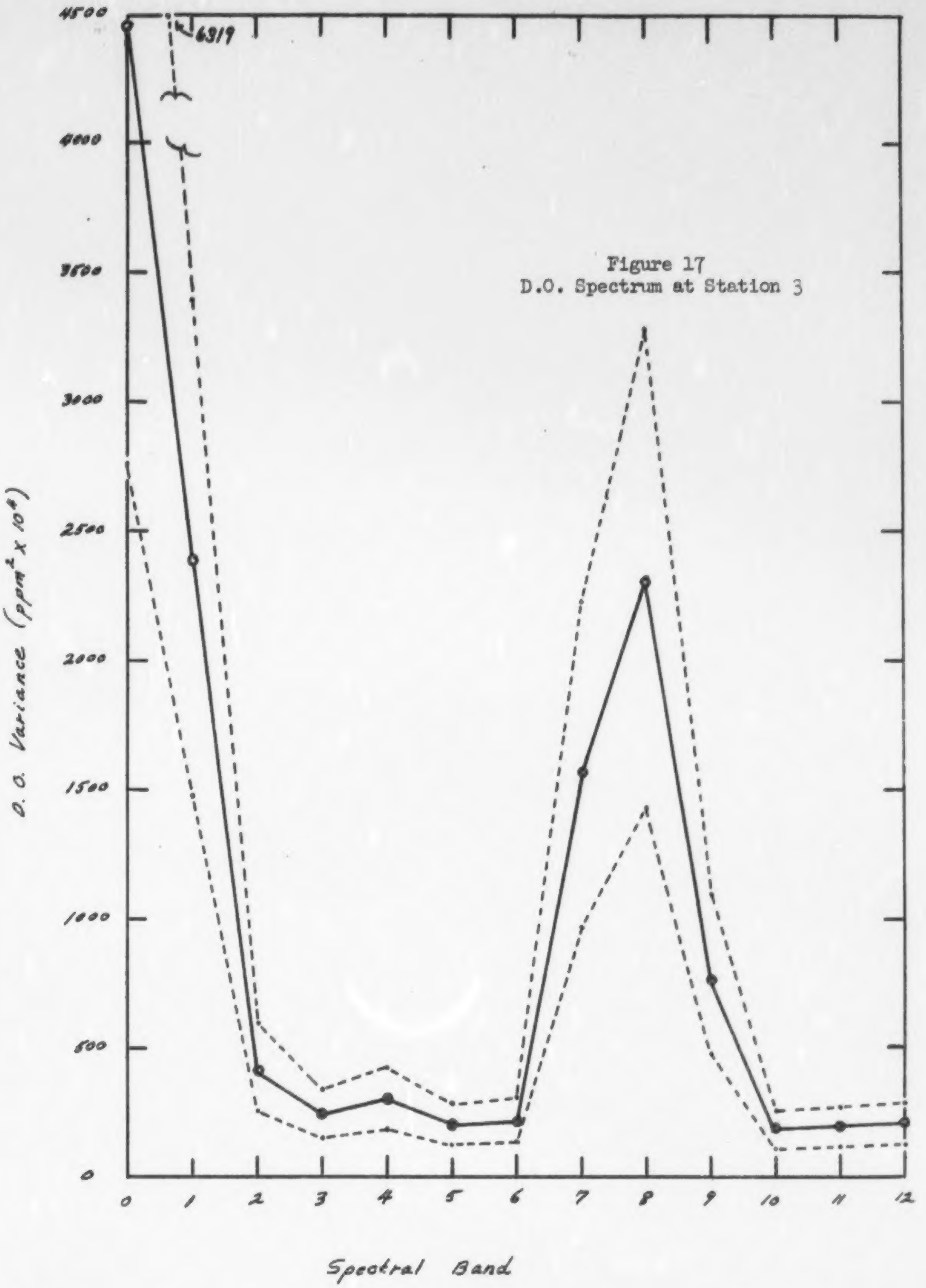


Figure 17
D.O. Spectrum at Station 3

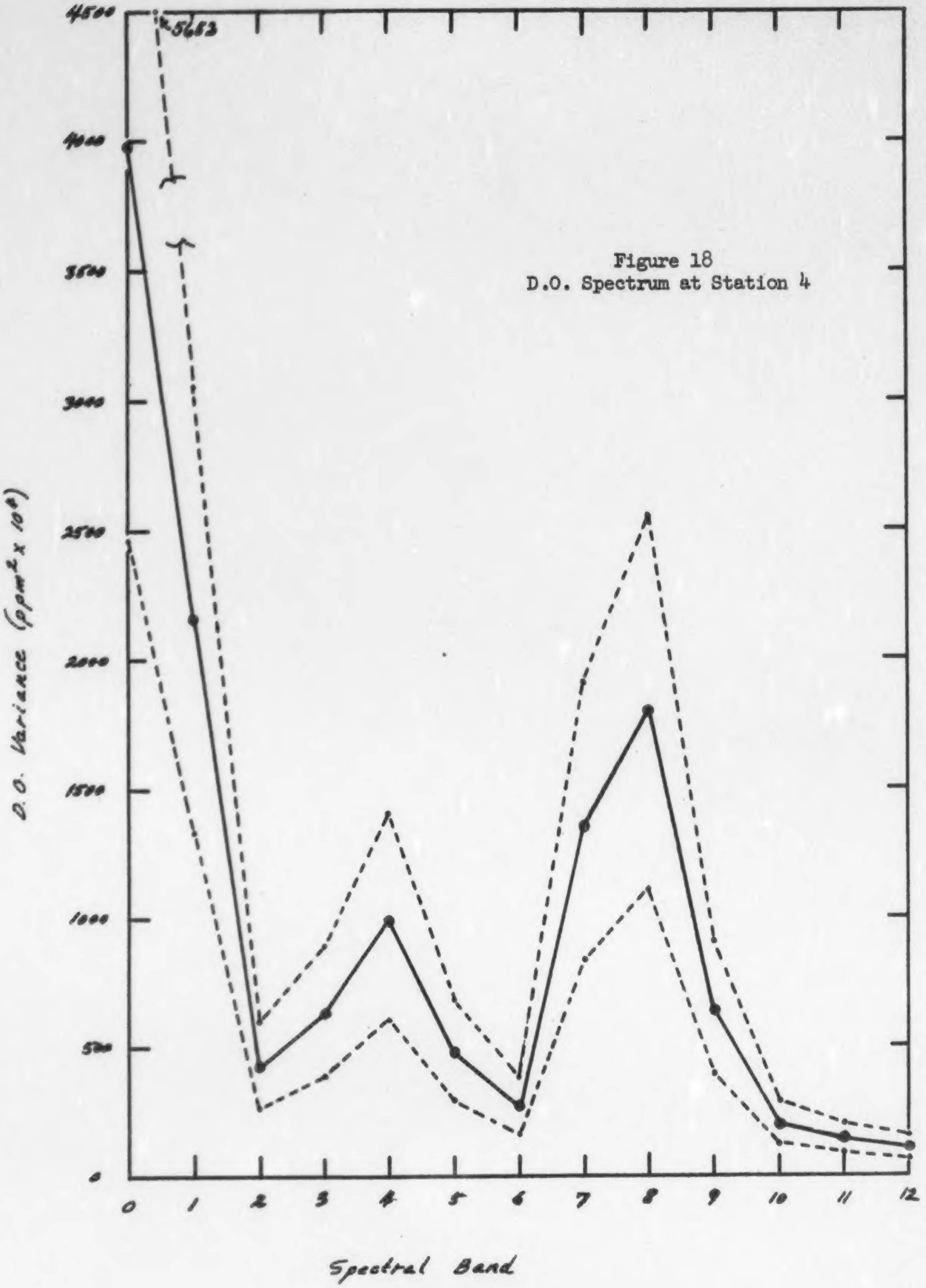


Figure 18
D.O. Spectrum at Station 4

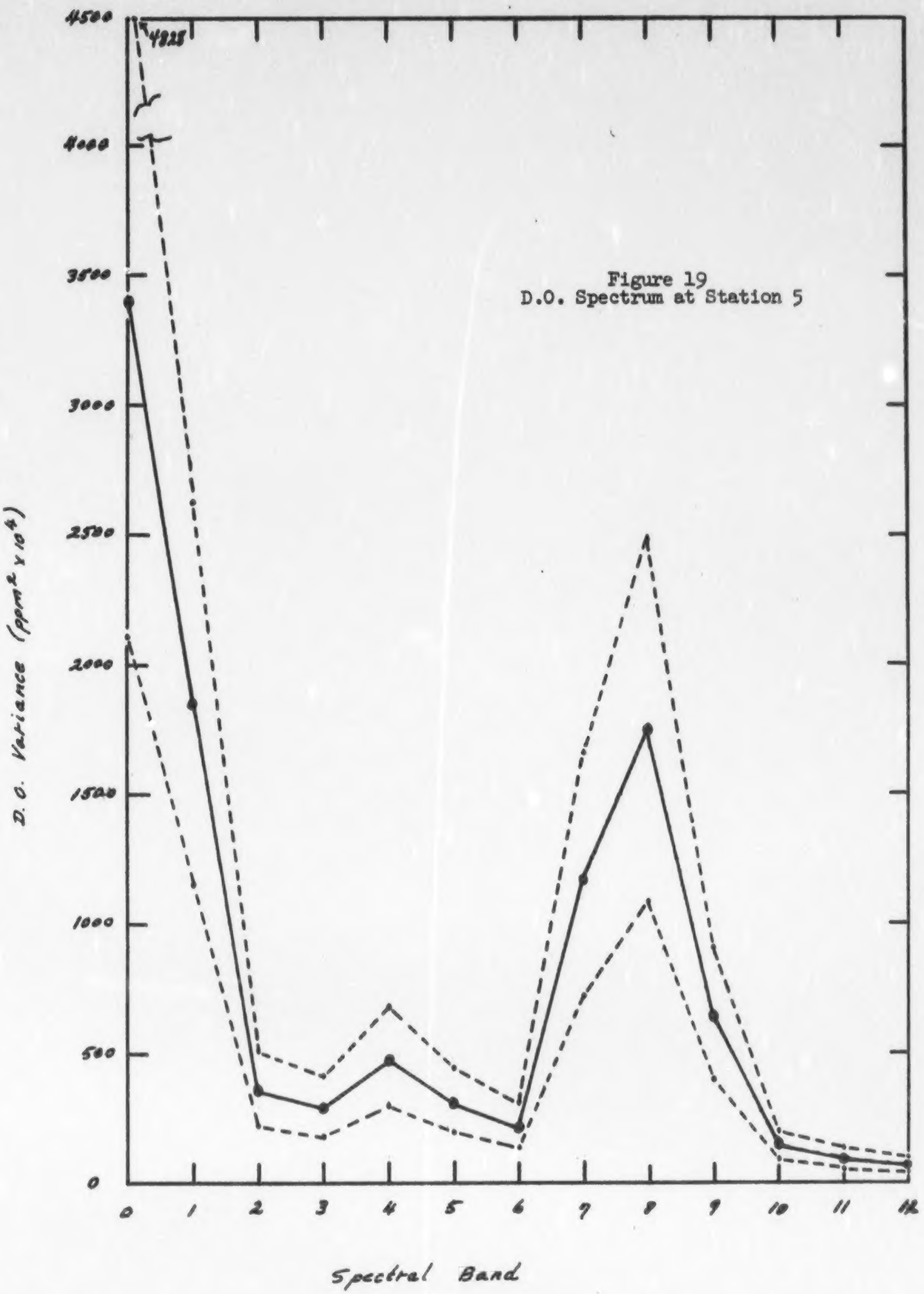


Figure 19
D.O. Spectrum at Station 5

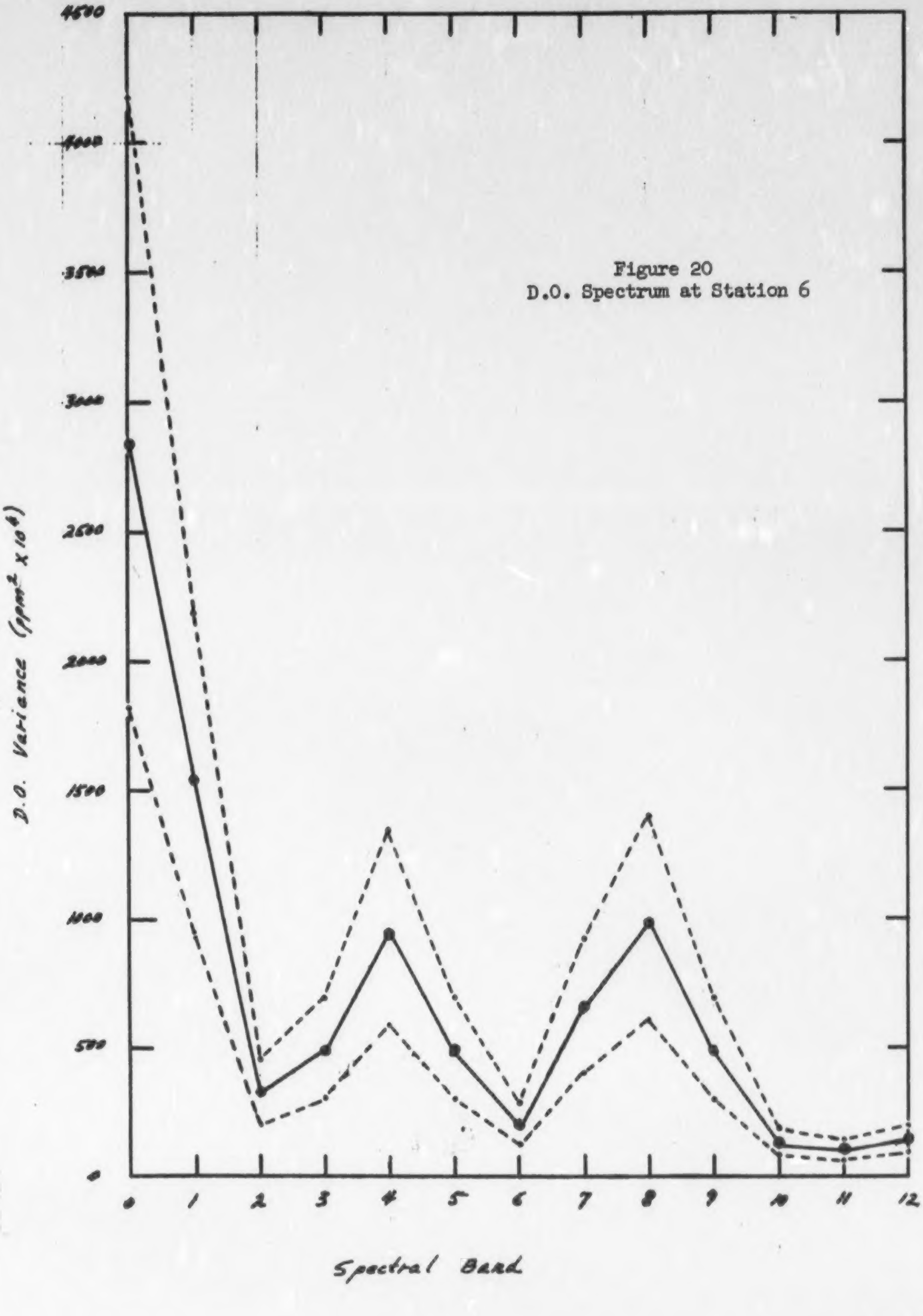


Figure 20
D.O. Spectrum at Station 6

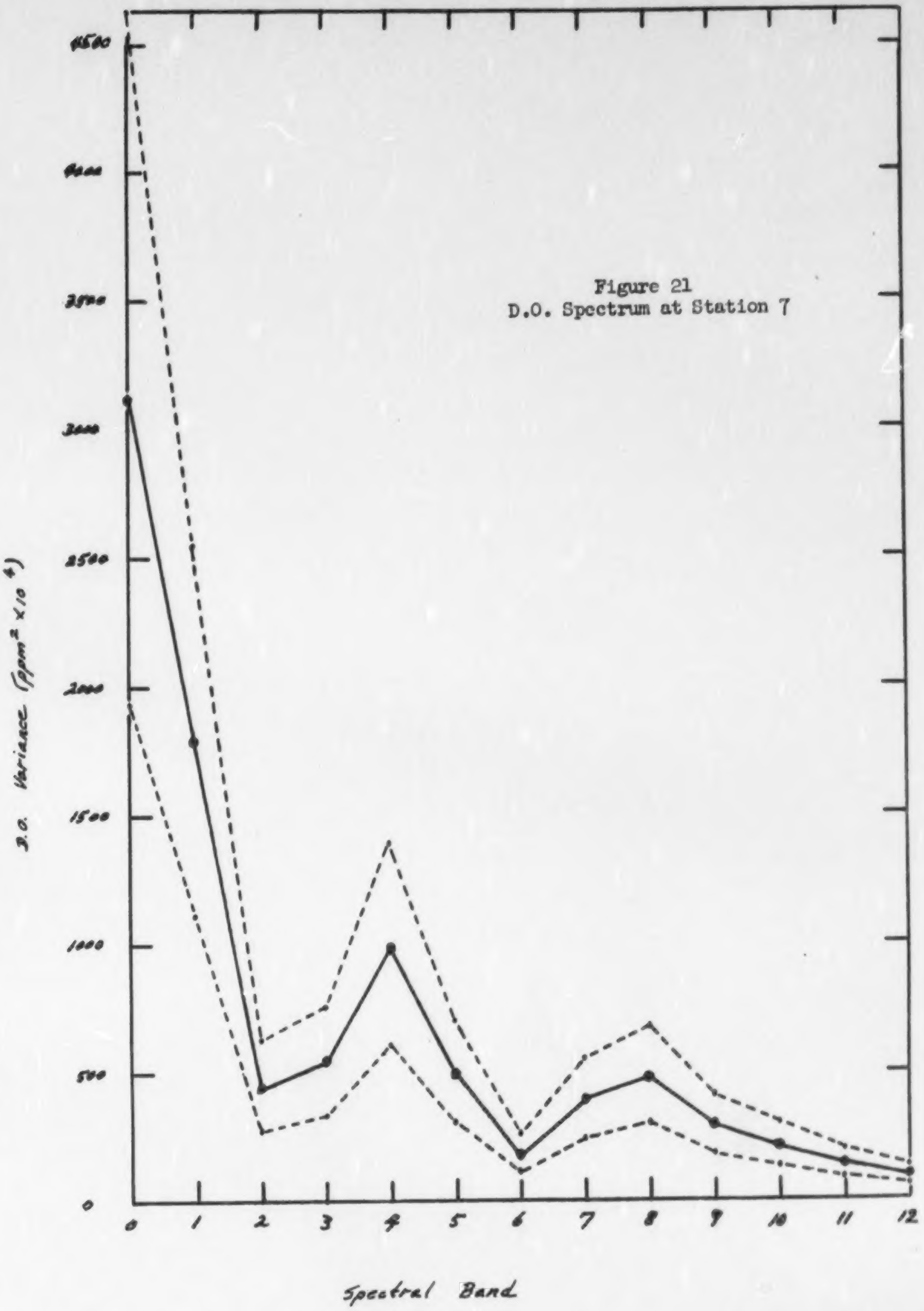


Figure 21
D.O. Spectrum at Station 7

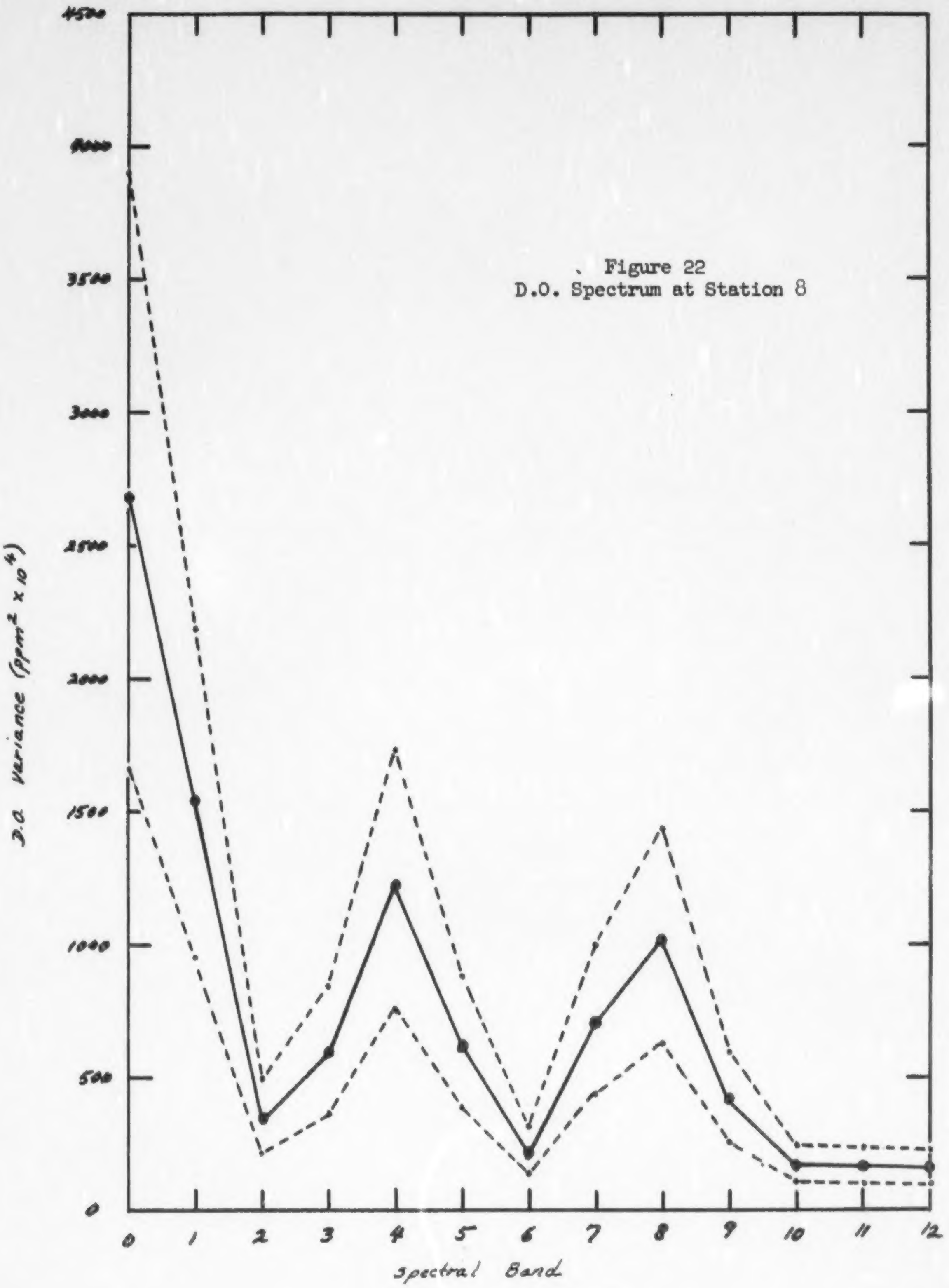


Figure 22
D.O. Spectrum at Station 8

variance, no significant diurnal effects, but very large semidiurnal variance. At Station 4 there is once more a very large total variance, and there is a significant diurnal peak as well as a somewhat larger semidiurnal variance. At Station 5 the total variance is less than at Stations 3 and 4, and the semidiurnal effects are much larger than the barely significant diurnal effects. At Station 6 the total variance has decreased once more, and the diurnal and semidiurnal effects are of about equal importance. Station 7 exhibits about the same total variance as Station 6, but the diurnal effects are considerably more important than the semidiurnal. At Station 8 the total variance has increased slightly, and the diurnal and semidiurnal effects are about the same size. Station 0, in the Anacostia River, has comparatively small long-period changes, and the variance is almost completely dominated by the semidiurnal effects.

The BOD spectral analysis results are presented in Figure 23 through 31. These results present some marked contrasts to the D.O. records as well as some similar effects. Station 1 exhibits only a very small total variance and no significant diurnal or semidiurnal effects; these results are in general similar to the D.O. spectrum. At Station 2 the total variance has increased slightly and there is a barely significant diurnal peak; there is no evidence of any shorter period fluctuations in BOD to account for the short-period D.O. fluctuations. Note also that the long-period dominance is not as pronounced in the BOD record as it is in the D.O. record. At Station 3 there is a moderate increase in total BOD variance, with a slight diurnal effect and a larger semidiurnal effect as in the D.O. record. The

BOD record is not dominated nearly as much by long-period effects as is the D.O. record. Station 4 exhibits a large increase in total variance and diurnal and semidiurnal effects of relative size similar to those exhibited by the D.O. records. At Station 5 the BOD spectrum is quite similar to that exhibited at Station 4; the BOD shows somewhat stronger diurnal effects than does the D.O. At Station 6 the semidiurnal effects and the long-period effects in the BOD record are of about the same magnitude; the diurnal peak is considerably smaller. The D.O. spectrum at this station shows that most of the D.O. variance is due to long-period effects. Stations 7 and 8 exhibit BOD spectra similar to those at Station 6, in marked contrast to the D.O. spectra which show the dominance of long-period effects and the diurnal effects to be more important than the semidiurnal effects. At Station 0 long-period fluctuations dominate the spectrum while semidiurnal effects are of only slight importance--again in marked contrast to the D.O. spectrum.

The spectra of the waste volume discharges are presented in Figures 32 through 35. While these spectra are not necessarily representative of the total quantity of oxygen demanding materials discharged, they probably do give a reasonably good picture of the relative importance of the periodicities in the discharge. All four spectra show the same characteristic: a small long-period effect, a dominant 24-hour fluctuation, and a small semidiurnal effect.

The spectrum of the solar radiation is presented in Figure 36. As might be expected the variance is dominantly diurnal, but with a small semidiurnal component.

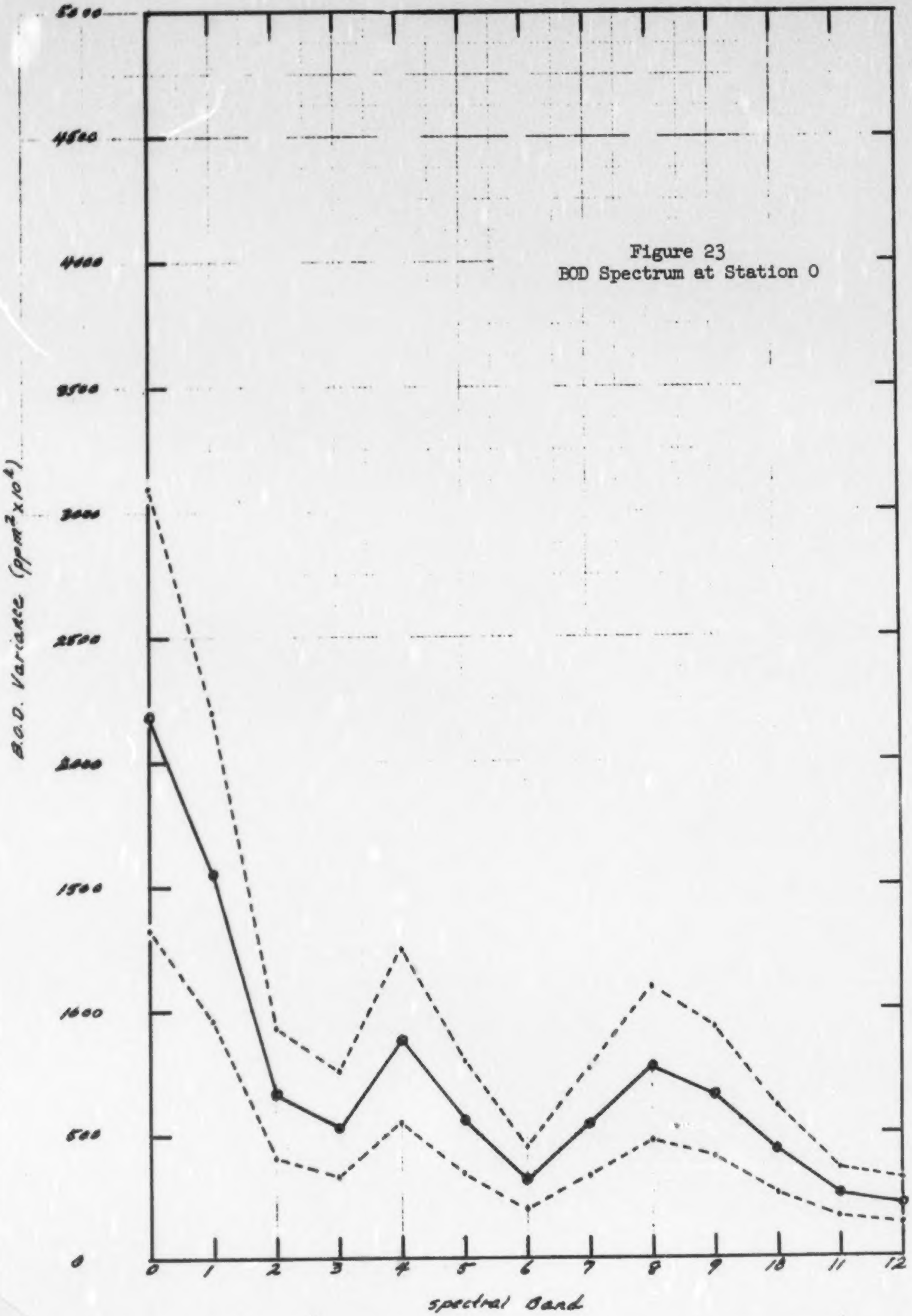


Figure 23
BOD Spectrum at Station 0

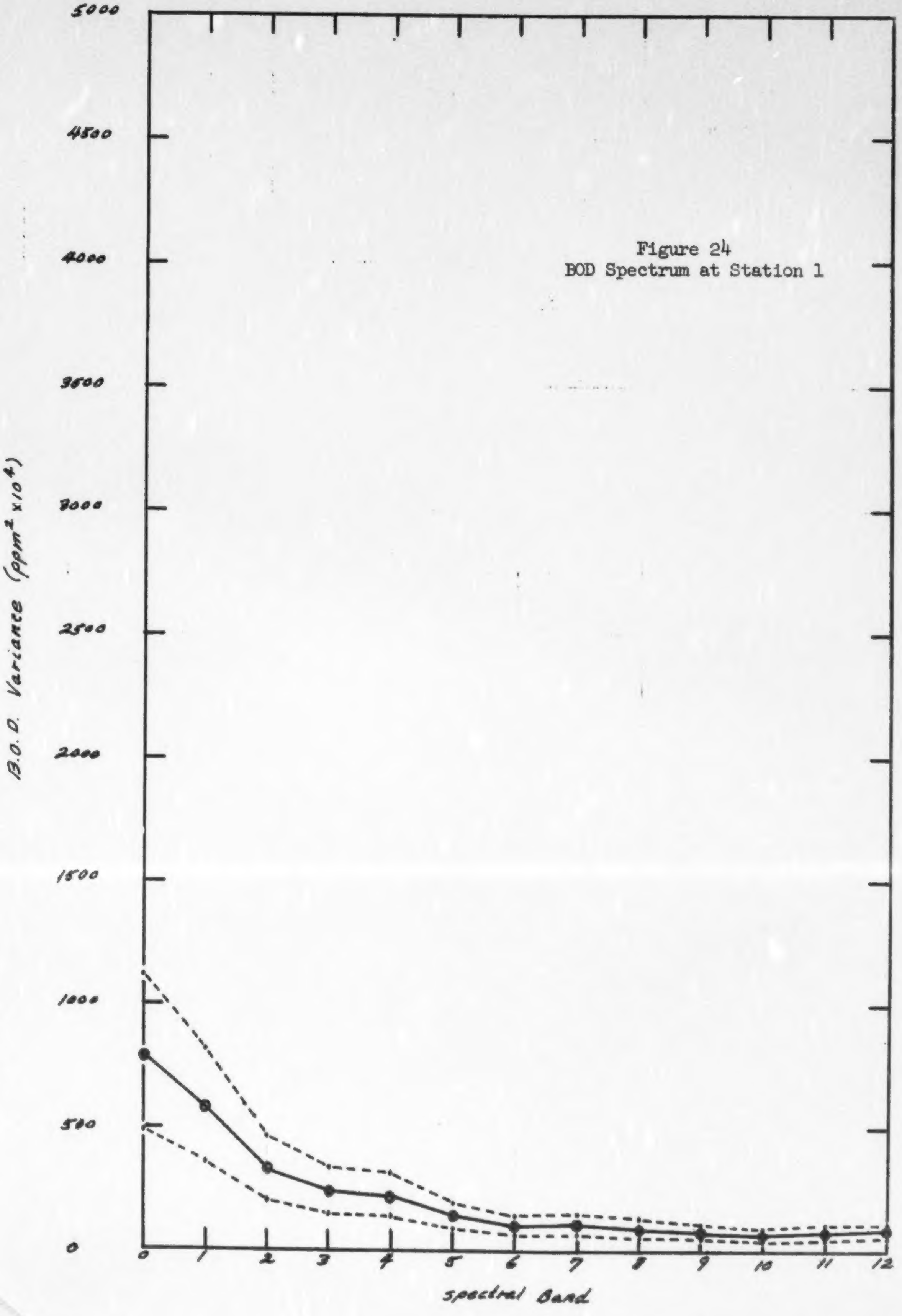


Figure 24
BOD Spectrum at Station 1

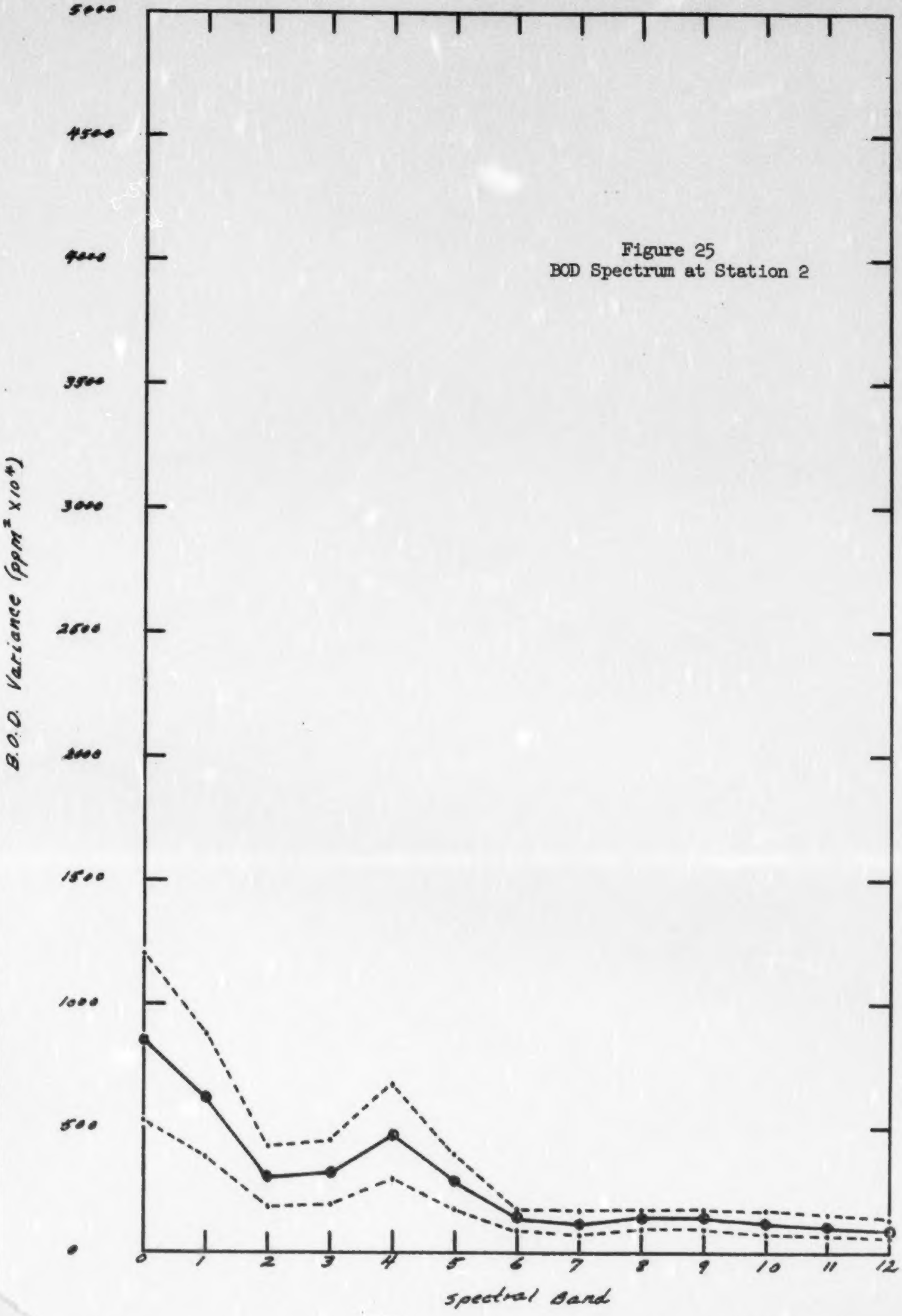


Figure 25
BOD Spectrum at Station 2

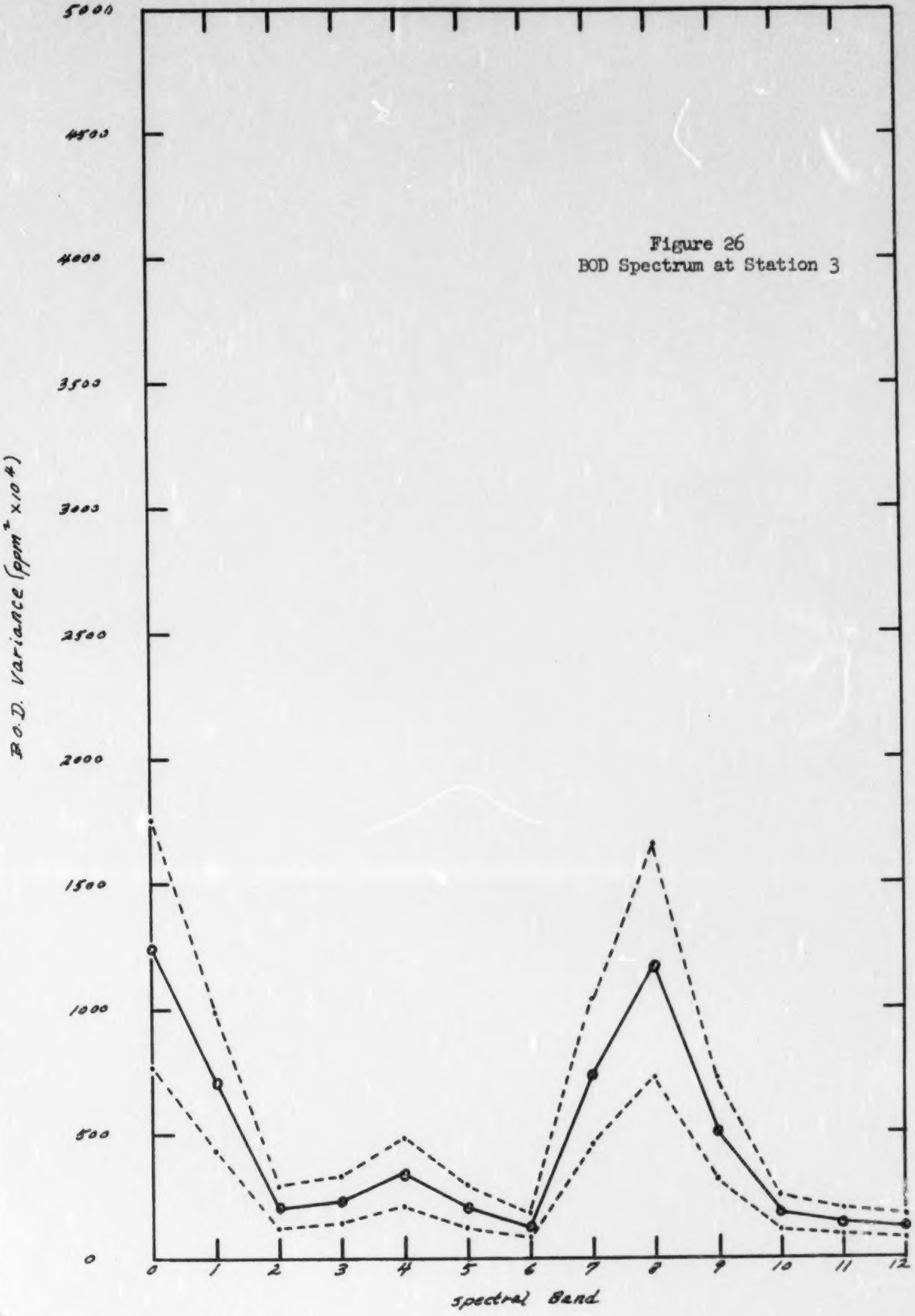


Figure 26
BOD Spectrum at Station 3

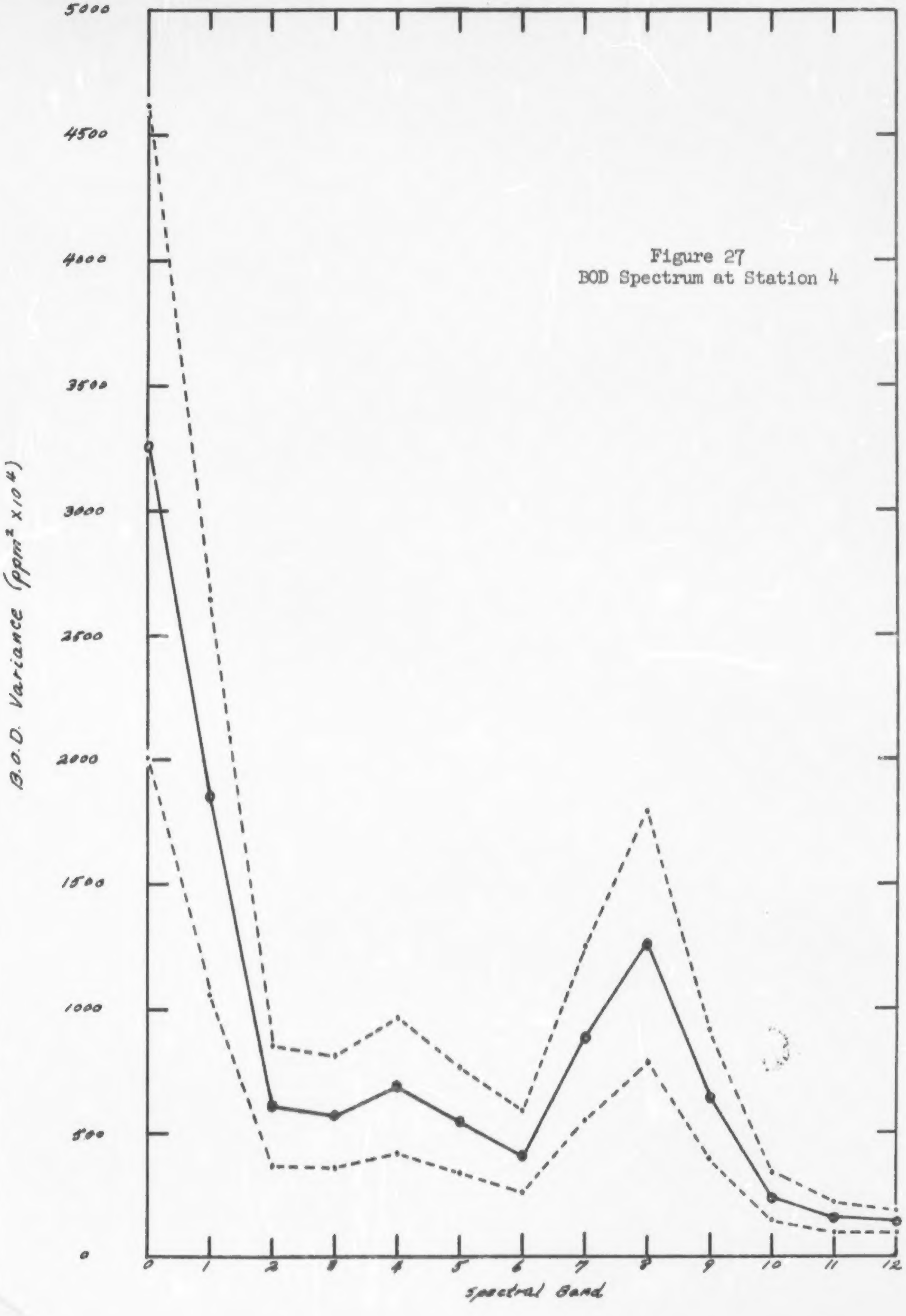


Figure 27
BOD Spectrum at Station 4

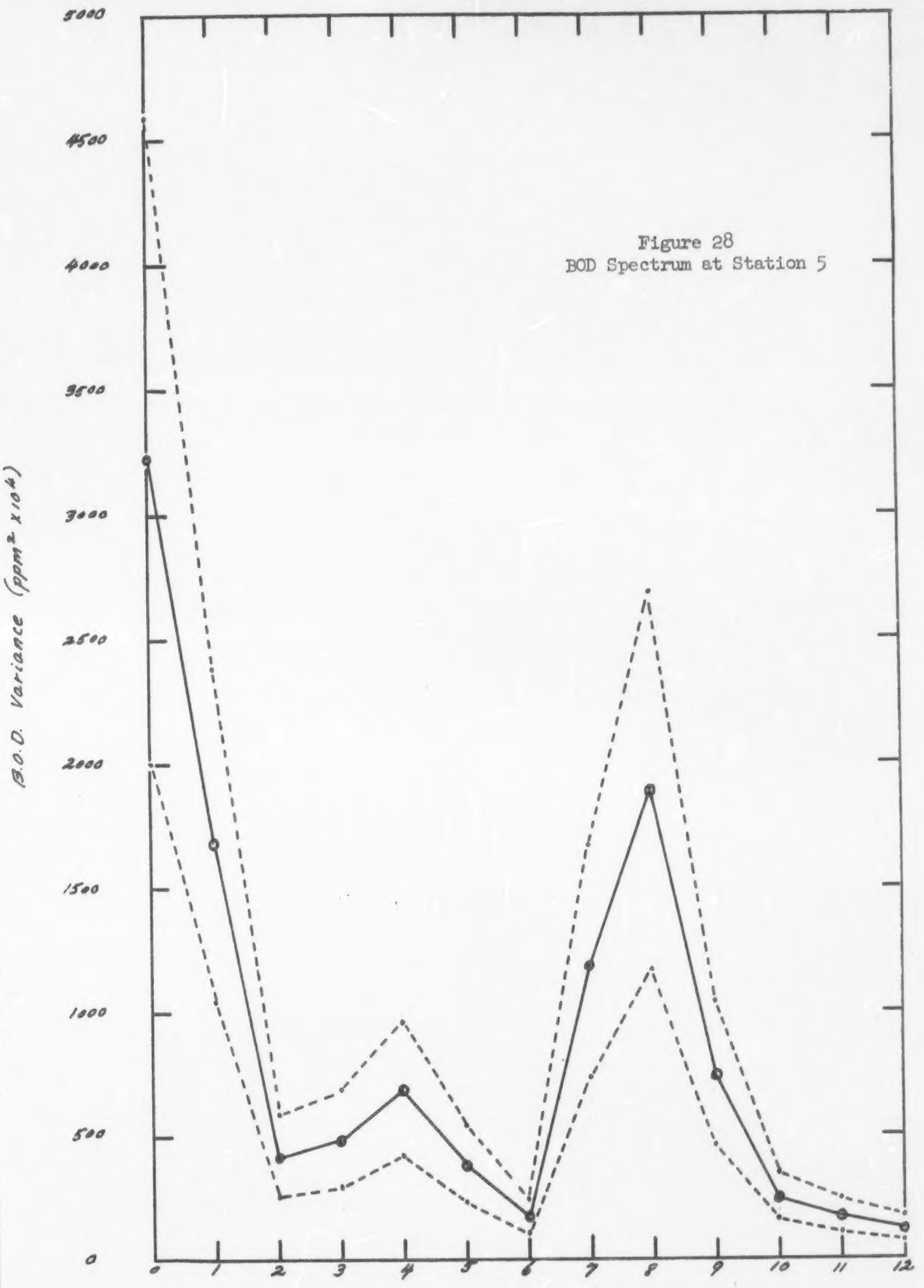


Figure 28
BOD Spectrum at Station 5

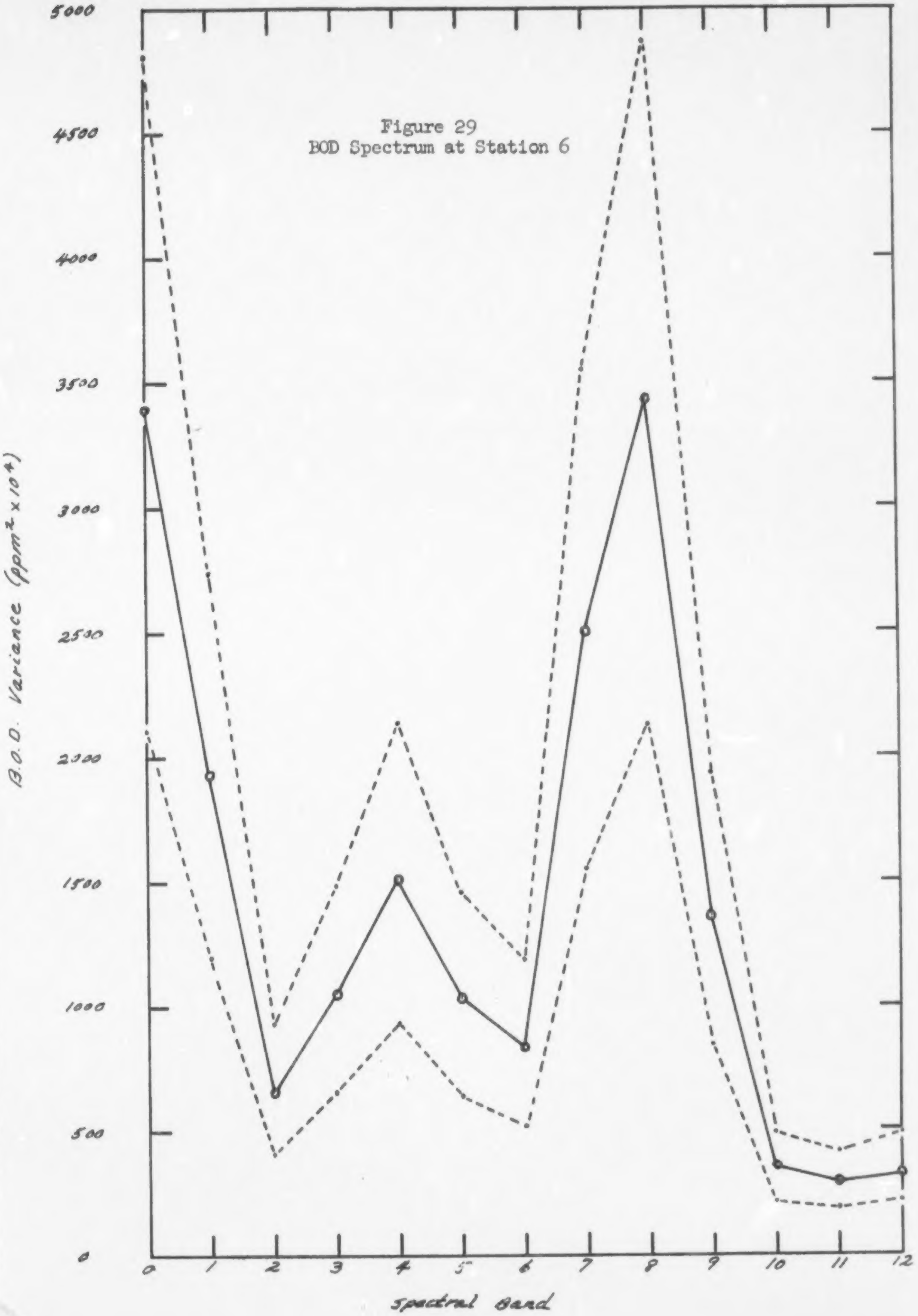


Figure 29
BOD Spectrum at Station 6

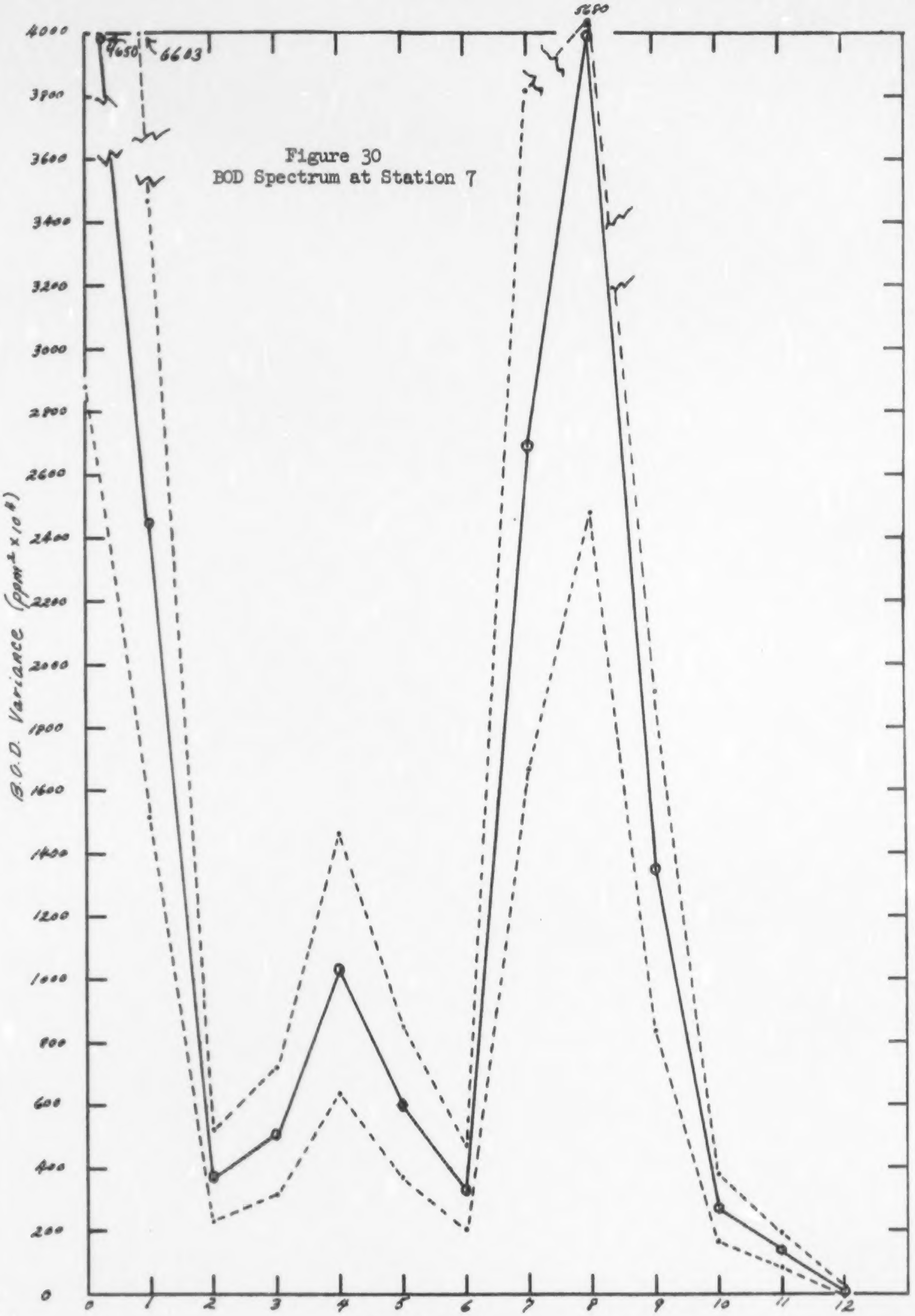


Figure 30
BOD Spectrum at Station 7

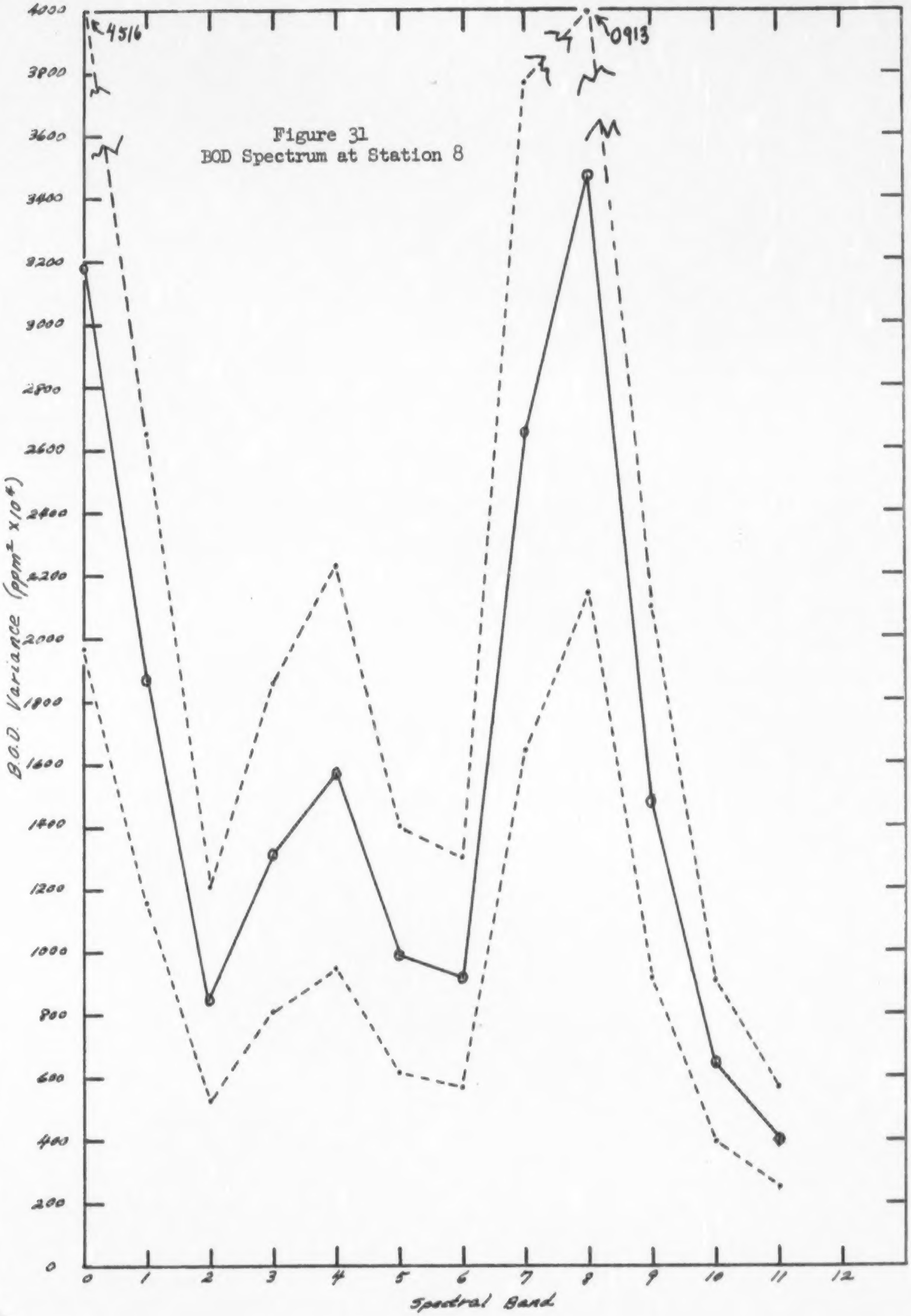


Figure 31
BOD Spectrum at Station 8

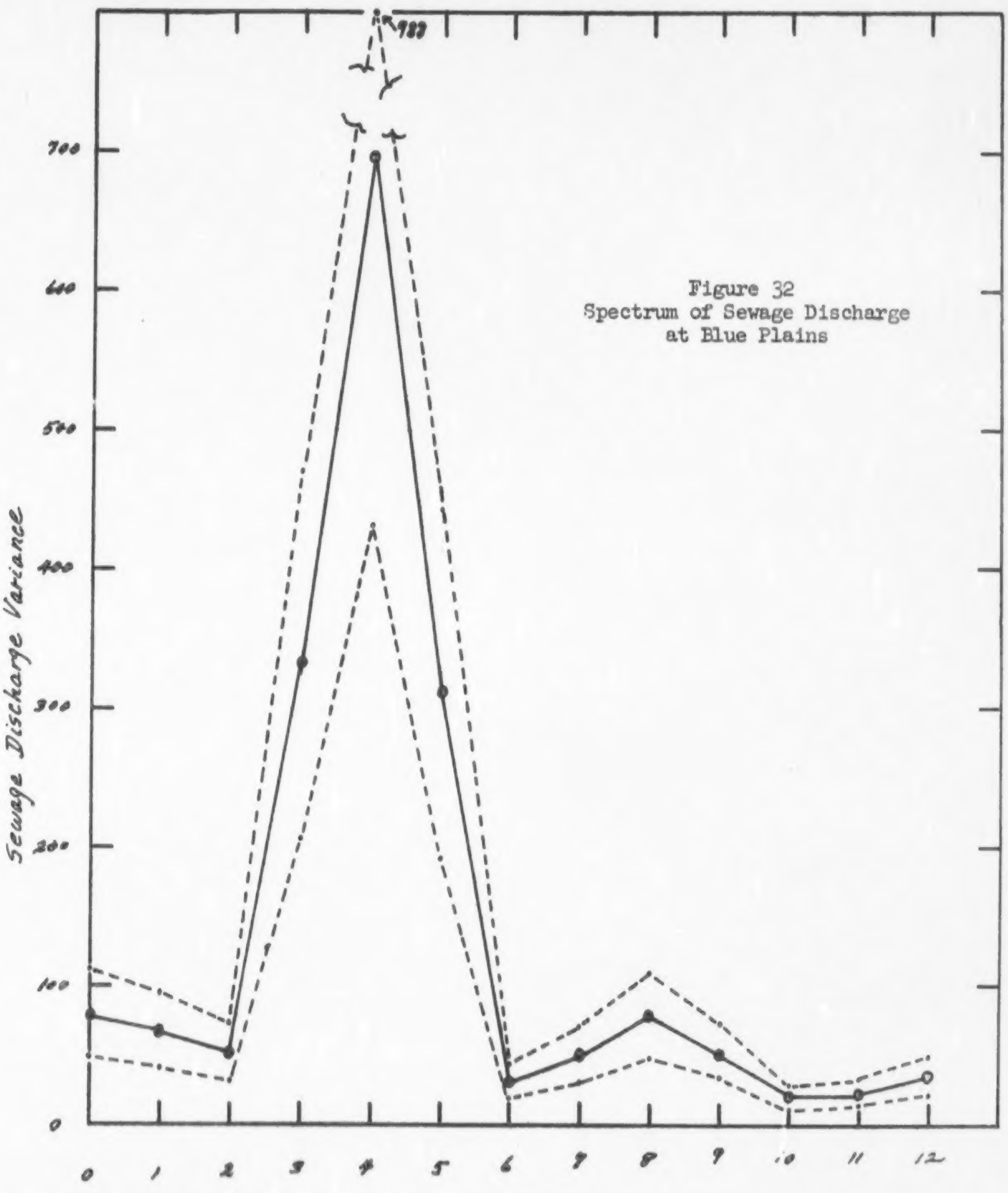


Figure 32
Spectrum of Sewage Discharge
at Blue Plains

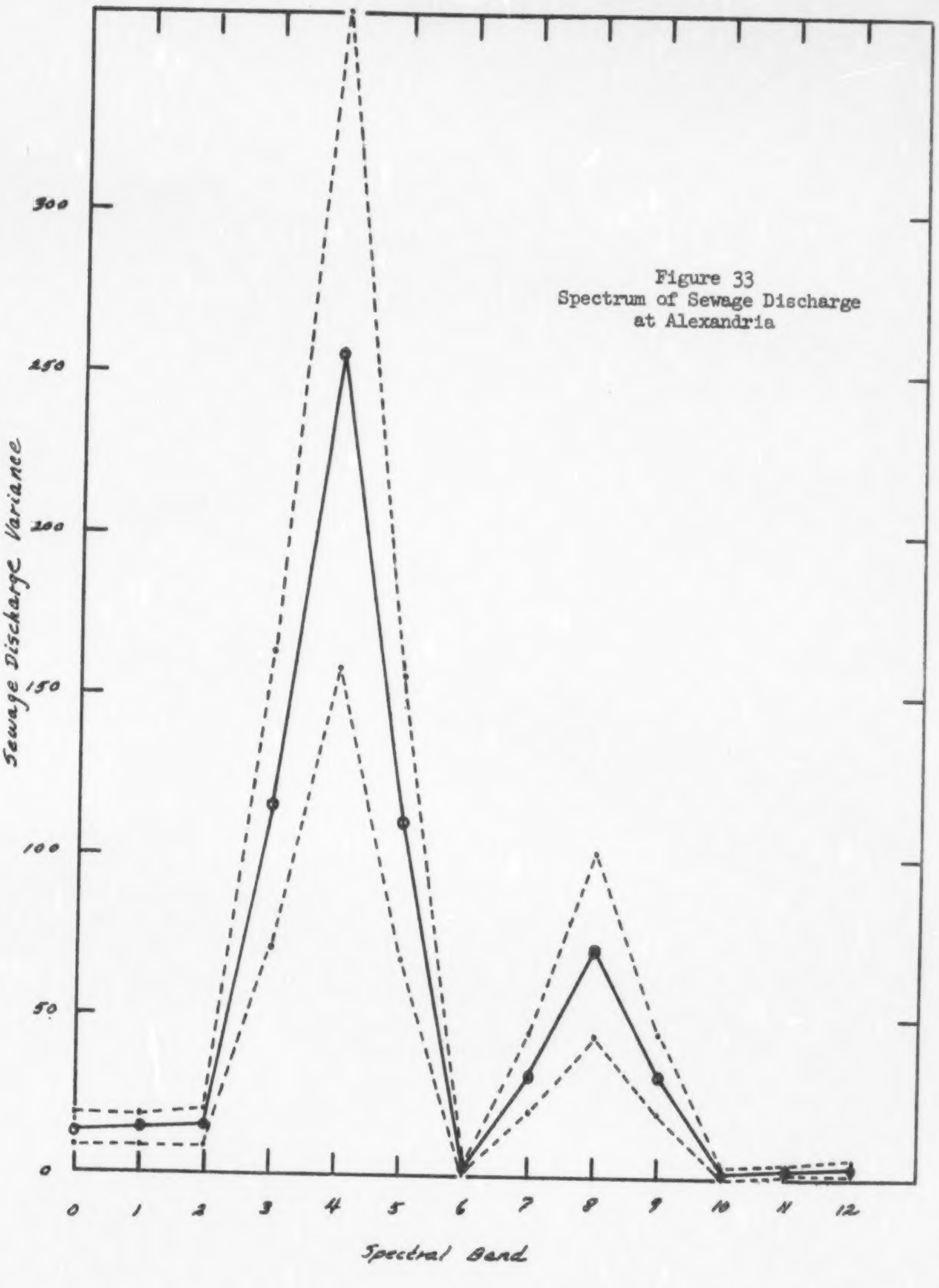


Figure 33
Spectrum of Sewage Discharge
at Alexandria

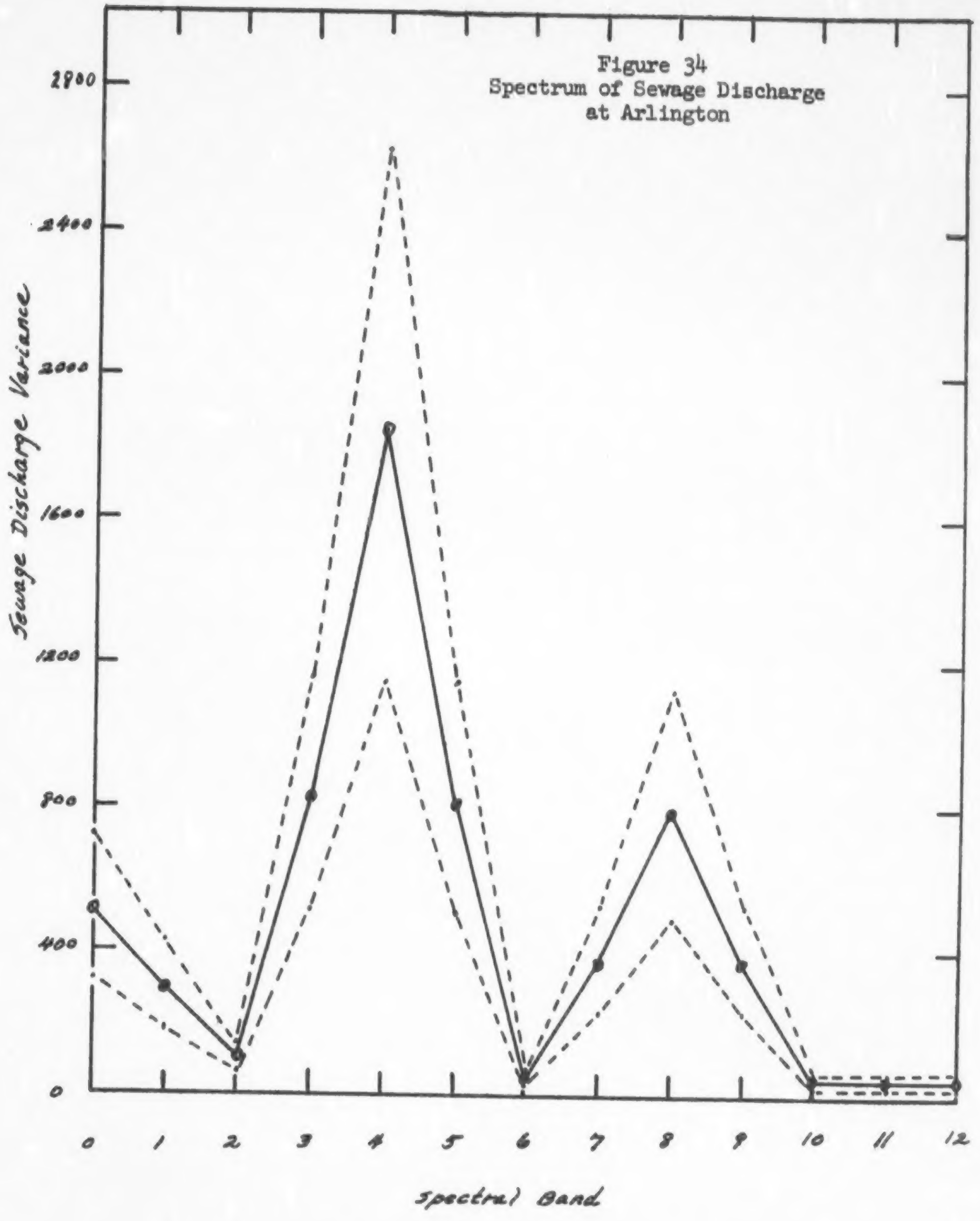


Figure 34
Spectrum of Sewage Discharge
at Arlington

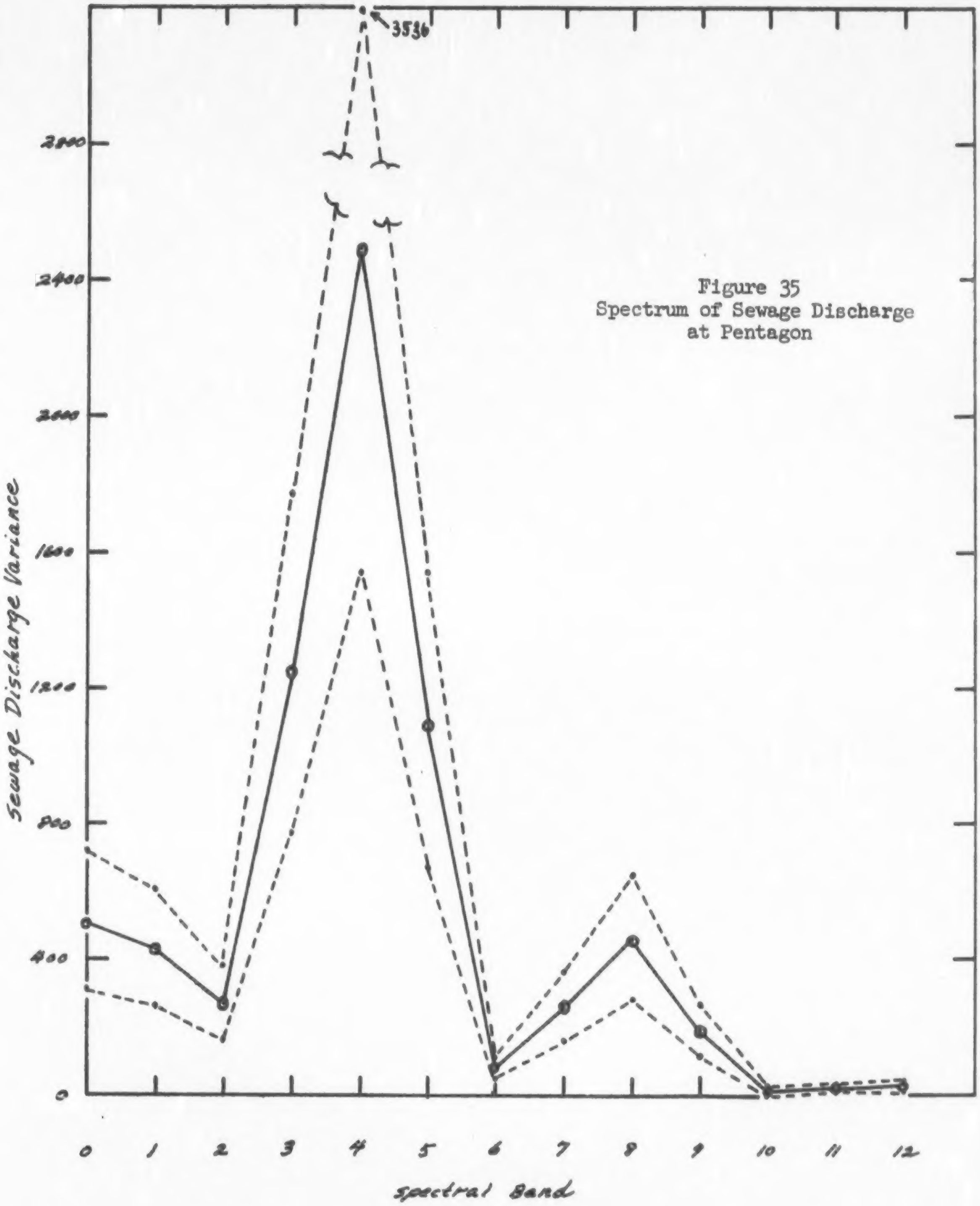


Figure 35
Spectrum of Sewage Discharge
at Pentagon

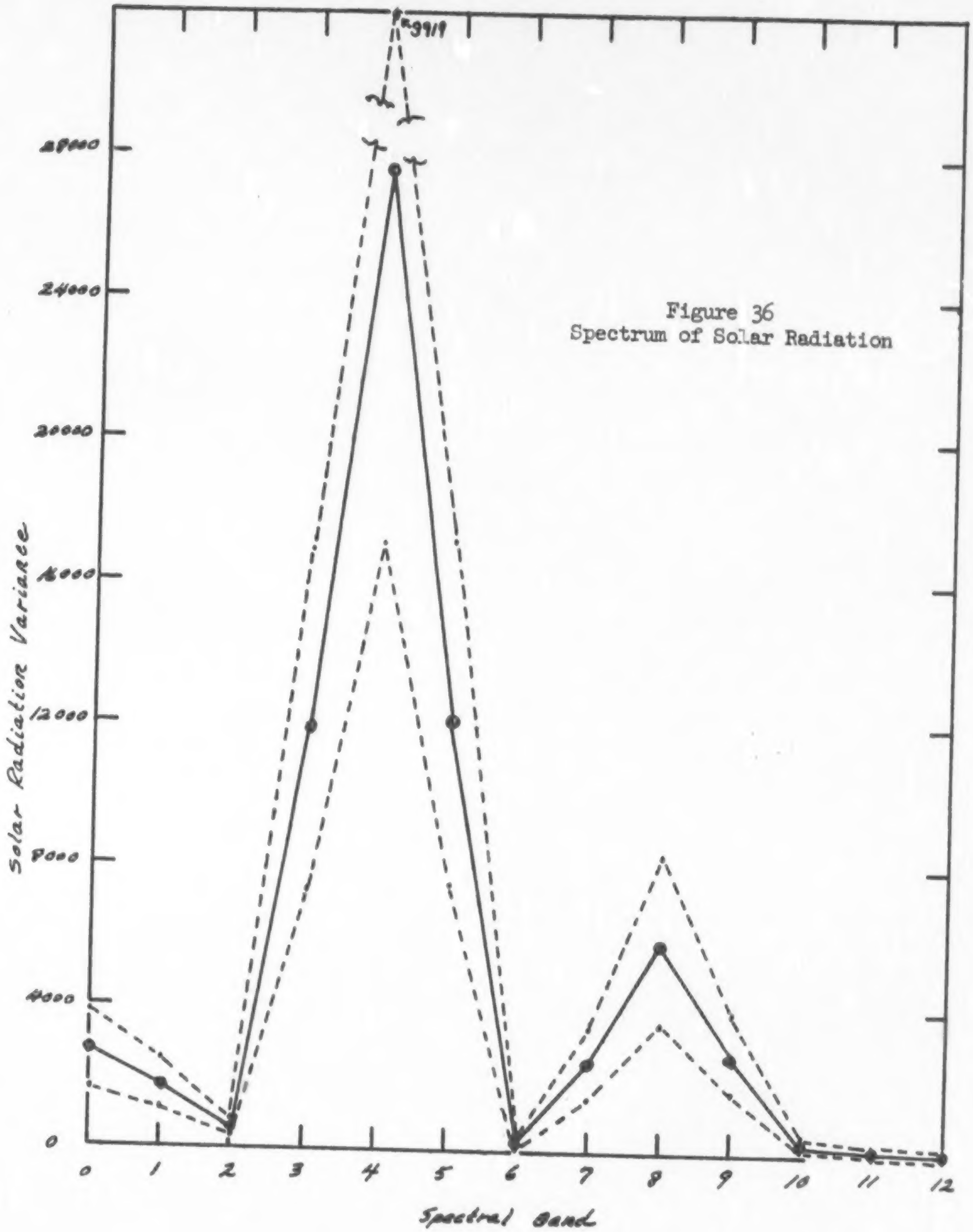


Figure 36
Spectrum of Solar Radiation

In Figure 37 the spectrum of the tide height at Alexandria is presented. Since all four gaging stations had records which produced practically identical records, only this one is presented for illustrative purposes. The tide at this point is almost entirely semidiurnal.

The river discharge spectrum is presented in Figure 38. The spectrum is entirely dominated by long-period effects. There is essentially no variance attributable to diurnal or semidiurnal effects.

Cross-Spectra

The cross-spectral results are of interest in this study in that they provide a means of calculating the frequency response functions and the total responses. The cross-spectrum of solar radiation with D.O. at Station 8 is presented in Figure 39 to illustrate what such a graph might be like. It will be noted that this cross-spectrum shows a pronounced diurnal effect and a negligible semidiurnal effect.

The calculated spectrum of the response of D.O. at the stream stations to fluctuations in stream BOD, sunlight, temperature, and the tide-river discharge combination are presented in Table XI.

The spectrum of D.O. response to sunlight shows progressive changes from upstream to downstream. From practically no response at Station 1 (and at Station [illegible], the response reaches a dominant diurnal fluctuation combined with a significant long-period fluctuation at Station 8. There is practically no semidiurnal response except at Station 2.

Table XI

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
0	0	886	11.4	106	0.190	0.640	8.7
	1	696	29.1	21.3	5.30	19.7	37.0
	2	375	11.7	21.0	11.8	10.7	61.7
	3	296	23.3	3.68	24.4	0.0777	79.3
	4	234	42.5	8.39	40.5	4.37	122
	5	170	13.2	2.02	18.1	19.7	68.5
	6	278	23.0	21.9	82.4	5.57	82.8
	7	1840	2.67	172	1010	6.67	1460
	8	2540	27.5	68.0	1320	47.5	2000
	9	794	23.1	4.46	254	5.86	419
	10	217	5.69	9.63	21.5	1.20	5.37
	11	94.3	2.63	11.4	50.5	8.17	-44.1
	12	0.0	0.20	1.70	109	13.6	-75.0
	Total	8420	216	452	2940	144	4220

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
1	0	1260	15.4	410	245	340	
	1	785	5.47	184	180	166	
	2	482	12.7	56.9	19.0	70.8	
	3	417	25.2	71.1	1.08	3.41	
	4	419	49.4	17.6	76.6	3.47	
	5	439	24.0	10.8	80.9	54.6	Not Run
	6	342	9.91	10.2	26.0	6.35	
	7	334	3.76	17.7	4.98	18.3	
	8	285	18.1	0.906	18.5	15.0	
	9	221	24.2	23.8	8.63	6.77	
	10	218	28.1	19.6	0.994	2.04	
	11	229	2.26	6.12	4.60	4.44	
	12	250	0.01	1.86	11.2	0.708	
	Total	5680	219	831	678	692	

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
2	0	1860	228	618	282	579	19.1
	1	1160	87.9	351	278	327	92.3
	2	531	4.13	24.7	4.54	38.9	65.5
	3	440	9.45	16.7	12.3	56.6	14.3
	4	651	29.3	46.0	22.5	37.0	35.2
	5	734	11.0	0.890	2.53	3.04	0.650
	6	499	0.998	56.4	2.96	5.09	7.74
	7	619	116	35.4	2.65	7.39	96.0
	8	740	226	18.3	143	27.7	170
	9	615	62.8	3.69	20.7	2.41	75.0
	10	723	15.6	0.315	14.6	4.10	0
	11	591	3.91	79.4	12.0	5.36	-14.1
	12	413	3.21	28.1	16.7	7.36	- 8.1
	Total	9580	798	1280	816	1100	554

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
3	0	4460	515	81.0	291	194	188
	1	2390	194	551	355	352	160
	2	417	18.0	11.4	84.0	32	31.2
	3	248	46.0	9.36	31.0	18.7	42.2
	4	307	108	95.4	166	1.72	42.6
	5	205	43.2	18.4	57.4	13.7	25.9
	6	219	1.01	67.2	9.28	20.2	105
	7	1570	3.18	929	232	38.0	1330
	8	2310	22.9	1350	289	10.3	1790
	9	761	15.0	367	26.2	13.5	345
	10	181	9.23	24.8	10.3	19.5	241
	11	191	22.4	9.35	1.86	0.757	-109
	12	208	17.5	86.5	11.6	10.2	-139
	Total	13500	1020	3600	1560	724	4050

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
4	0	3980	874	253	245	54.1	442
	1	2160	402	73.4	331	488	346
	2	428	2.70	7.22	171	78.4	79.8
	3	626	347	42.7	417	15.5	177
	4	989	702	251	847	67.2	765
	5	481	236	61.8	271	11.1	242
	6	270	47.0	26.8	150	4.09	78.7
	7	1350	15.2	286	13.7	53.2	1020
	8	1800	12.6	580	8.42	25.6	1460
	9	636	.234	106	9.78	19.2	380
	10	196	49.5	0.349	3.08	90.7	8.03
	11	133	13.9	0.818	2.73	30.2	-46.2
	12	108	1.92	0.134	3.23	0.755	-65.0
	Total	13200	2700	1690	2470	938	4890

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
5	0	3400	624	874	381	147	382
	1	1850	275	591	278	278	399
	2	363	41.4	27.2	51.4	24.9	115
	3	294	150	47.0	168	4.02	202
	4	484	339	286	407	37.3	627
	5	313	125	72.6	85.0	32.1	147
	6	215	17.7	21.1	9.4	3.63	69.6
	7	1170	67.7	372	538	39.7	1060
	8	1750	107	586	813	41.2	1410
	9	646	32.7	70.7	117	30.1	287
	10	141	8.94	22.3	3.57	12.5	60.6
	11	89.3	5.97	30.0	47.4	3.32	-16.9
	12	68.4	27.0	9.71	28.0	0.109	-16.3
	Total	10800	1820	3010	2930	654	4730

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen (ppm^2 x 10^4)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
6	0	2840	896	620	207	109	432
	1	1540	334	459	221	305	328
	2	325	3.58	8.07	42.3	53.5	30.2
	3	497	319	57.7	312	17.0	143
	4	941	703	233	715	24.9	523
	5	497	285	76.2	280	5.77	79.6
	6	201	23.4	0.889	11.1	4.11	17.9
	7	657	28.4	83.2	202	46.3	367
	8	980	32.4	73.6	226	41.3	575
	9	488	29.8	3.35	0.32	59.5	173
	10	126	7.28	12.7	1.53	17.1	16.9
	11	107	17.4	15.2	3.76	14.9	-9.44
	12	142	0.867	5.7	0.54	9.30	-9.70
	Total	9340	2680	1650	2220	708	2670

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
7	0	3120	723	446	77.9	14.6	568
	1	1790	454	738	140.0	235	328
	2	437	112	187	82.1	63.2	30.8
	3	545	307	205	358	12.3	91.8
	4	981	757	616	820	45.5	640
	5	494	351	198	243	18.7	153
	6	175	32.4	7.33	1.36	7.55	6.1
	7	396	0.527	442	34.3	92.4	117
	8	475	0.132	635	91.1	18.8	179
	9	294	3.23	14.9	6.71	45.5	41.3
	10	204	44.7	19.8	5.70	11.8	45.8
	11	137	27.1	14.2	17.3	1.77	3.1
	12	99.6	4.82	197	22.1	0.977	6.5
	Total	9150	2820	3720	1900	568	2210

Table XI (Continued)

Response of Stream Dissolved Oxygen to Driving Parameters

Station	Band Number	Variance in Stream Dissolved Oxygen ($ppm^2 \times 10^4$)					
		Observed	Response Related to:				
			Sunlight Variance	Stream BOD Variance	Temperature Variance	River Discharge Variance	River-Tide Variance
8	0	2680	416	0.133	340	301	881
	1	1540	508	546	271	329	407
	2	344	41.5	45.5	33.2	57.6	354
	3	591	441	103	320	15.9	115
	4	1220	1030	359	919	38.9	878
	5	619	430	86.9	295	22.3	147
	6	213	14.8	1.55	11.7	35.5	46.5
	7	701	5.51	208	217	0.432	332
	8	1010	21.0	298	371	31.1	479
	9	420	19.5	32.6	60.5	68.0	122
	10	173	13.8	1.81	46.5	2.58	4.33
	11	168	12.9	17.0	110	10.1	24.8
	12	158	1.17	8.82	144	4.41	40.3
	Total	9840	2960	1710	3140	917	3830

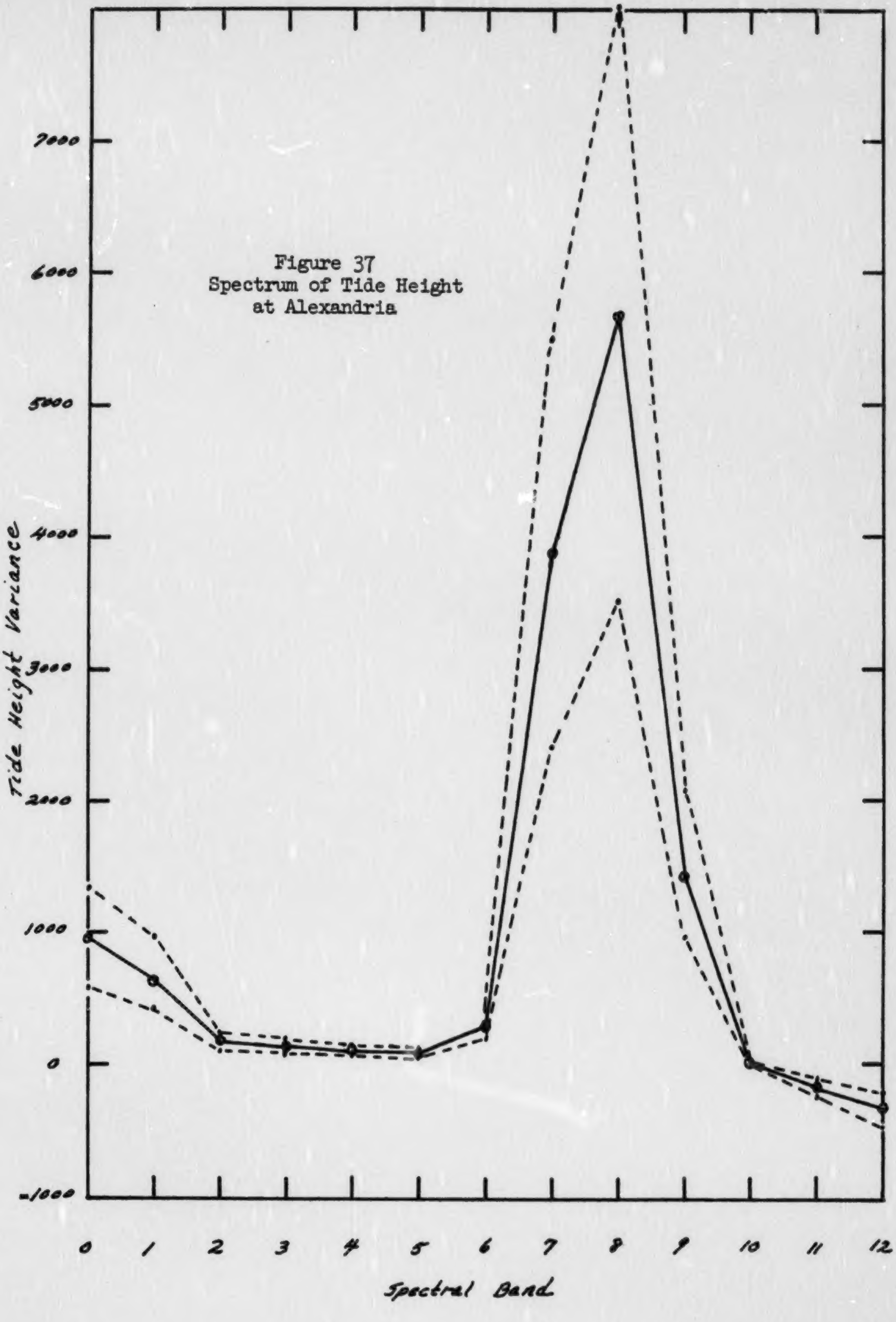


Figure 37
Spectrum of Tide Height
at Alexandria

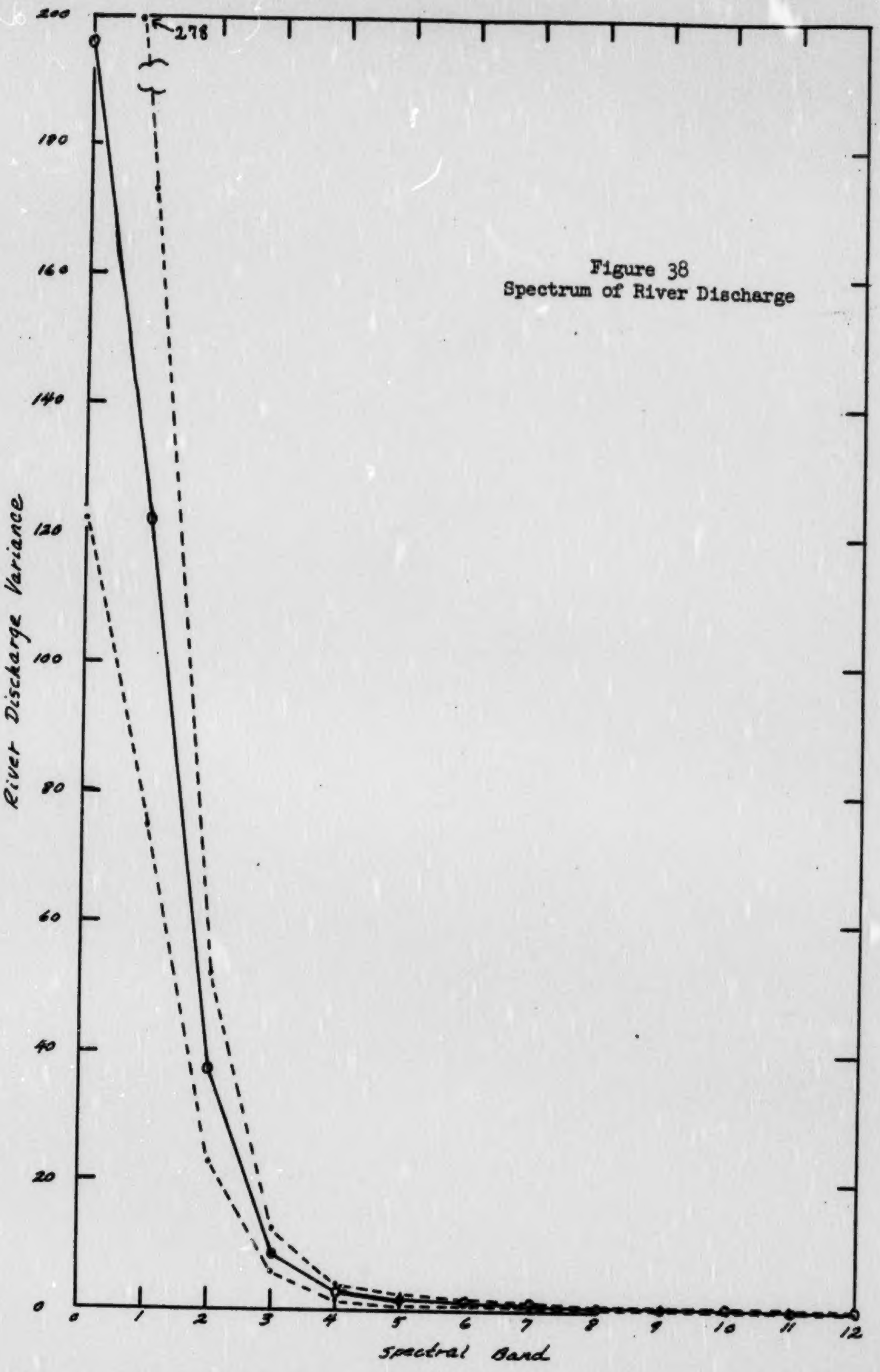


Figure 38
Spectrum of River Discharge

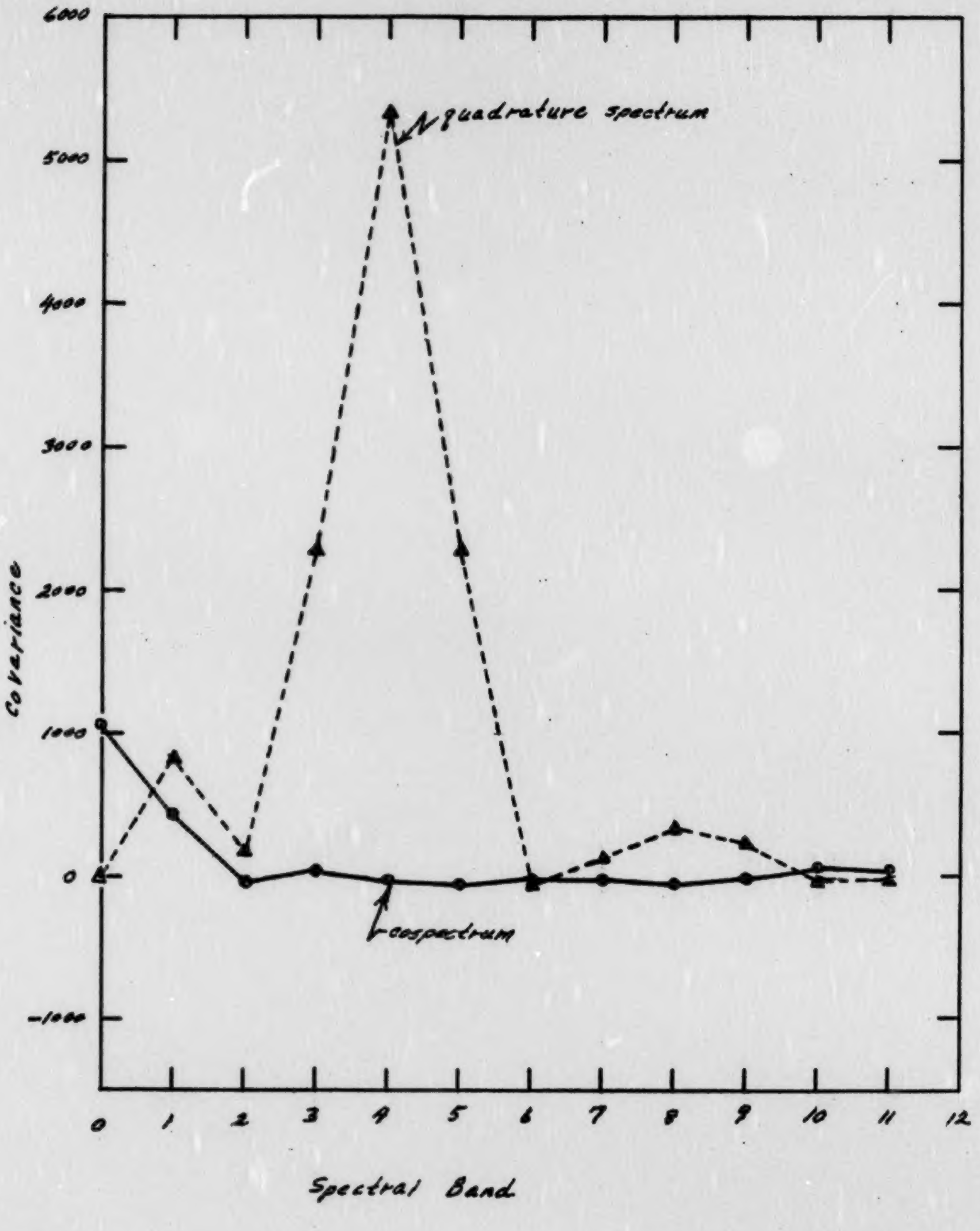


Figure 39
Cross-Spectrum of Solar Radiation
and D.O. at Station 8

The D.O. response spectrum to BOD also exhibits progressive changes. There is only a slight semidiurnal effect at Station 0, and some rather small long-period changes at Stations 1 and 2. Beginning at Station 3 there is a sequence of dominant semidiurnal and diurnal effects in which the diurnal effect dominates the semidiurnal effect at Station 6, the Blue Plains sewage outfall. There is also an increasing long-period fluctuation as Station 6 is approached.

The response of D.O. to temperature shows long-period trends and both diurnal and semidiurnal effects; the diurnal effects dominate at most stations. Since the temperature itself is controlled primarily by sunlight and river discharge, this is quite reasonable.

The combined response of D.O. to the river discharge and tide exhibits pronounced long-period and semidiurnal effects, with the semidiurnal effects dominating.

Descriptive Statistics

Each D.O. record was also processed by the procedures of statistical statics. Some of these results are presented in Table XII. The stations all exhibit standard deviations close to one (1) ppm. All stations with low mean values are skewed toward the higher range, and all stations with high means are skewed toward the lower range. The stations with high means have quite peaked distributions, while the others are nearly Gaussian (kurtosis = 0). The variances are highest when the mean values represent about 4 ppm (50 percent-saturation) and are smaller at both the high and low mean values.

Table XII

Descriptive Statistics of D.O. Records

Station	Mean(ppm)	Variance	Standard Deviation	Skewness	Kurtosis
0	2.29	.8423	.918	0.437	0.317
1	6.52	.5681	.754	-0.066	1.631
2	6.36	.9576	.979	-0.660	5.025
3	4.60	1.3467	1.16	0.106	0.104
4	3.29	1.3157	1.15	0.345	0.394
5	2.70	1.0784	1.04	0.225	-0.094
6	2.68	.9341	.966	0.334	0.227
7	2.53	.9148	.957	0.298	0.066
8	2.83	.9837	.992	0.194	0.032

DISCUSSION OF RESULTS

DESCRIPTIVE STATISTICS OF D.O. RECORDS

There are two aspects of the D.O. frequency distributions which are of considerable importance for the purposes of this report: the skewness and the variance. The skewness associated with the low and moderate mean D.O.'s indicates extremely low D.O. values should occur less frequently than extremely high D.O. values at these stations. The frequency distribution at Station 5 is typical of these stations and is shown in Figure 40. It should also be noted that some of this type of skewness persists for means as high as 4.60 ppm, although the skewness is quite small for this high mean. The variance, as shown in Table XII, is largest in association with means representing about 50-percent saturation. These results are presented graphically in Figure 41. A curve has been sketched merely to show the trend of these results in terms of mean D.O. It might be expected that the variance would be more a function of the physical dimensions of the system of the mean D.O.; this does not appear to be the case. The variances at Stations 2, 5, 6, 7, and 8 are similar, but there is a great variety in the cross sections. The same is true of Stations 3 and 4.

The reasons for the skewness and variance characteristics may lie in the relation of the mean value to the limits which the D.O. can reach; that is: the saturation value and the zero value. Mean values near the saturation limit would generally be associated with a low degree of pollution and relatively small oxygen use; when the saturation value is exceeded, there is a tendency for oxygen to be lost to the atmosphere and for the saturation value to be regained. Under these conditions a low variance and some skewing in the direction of lower values would be expected. Low mean D.O.'s would be assciated with a moderately high degree of pollution. Oxygen would be consumed quite rapidly, but the process of reaeration would also be at its most efficient level. The exact opposite of the situation near saturation would exist. Again, a low variance (because oxygen would be consumed nearly as fast as it entered) would be combined with some skewing toward the higher D.O. values. At moderate mean D.O. values, the processes of reaeration and deoxygenation would be competing, and slight changes in reaeration or in waste concentration would be reflected immediately in the D.O. record. A high variance and very little skewness, if any, would be expected.

The relationships of skewness and variance to the mean D.O. are of considerable significance in the determination of the waste assimilation capacity. A D.O. in the range of 50-percent saturation is usually regarded as a desirable value for which to aim. This is in the range of mean values which is associated with the highest variances. However, any tendencies toward a low mean D.O. will be associated with skewing toward the higher values, so that catastrophically low D.O.'s will be infrequent.

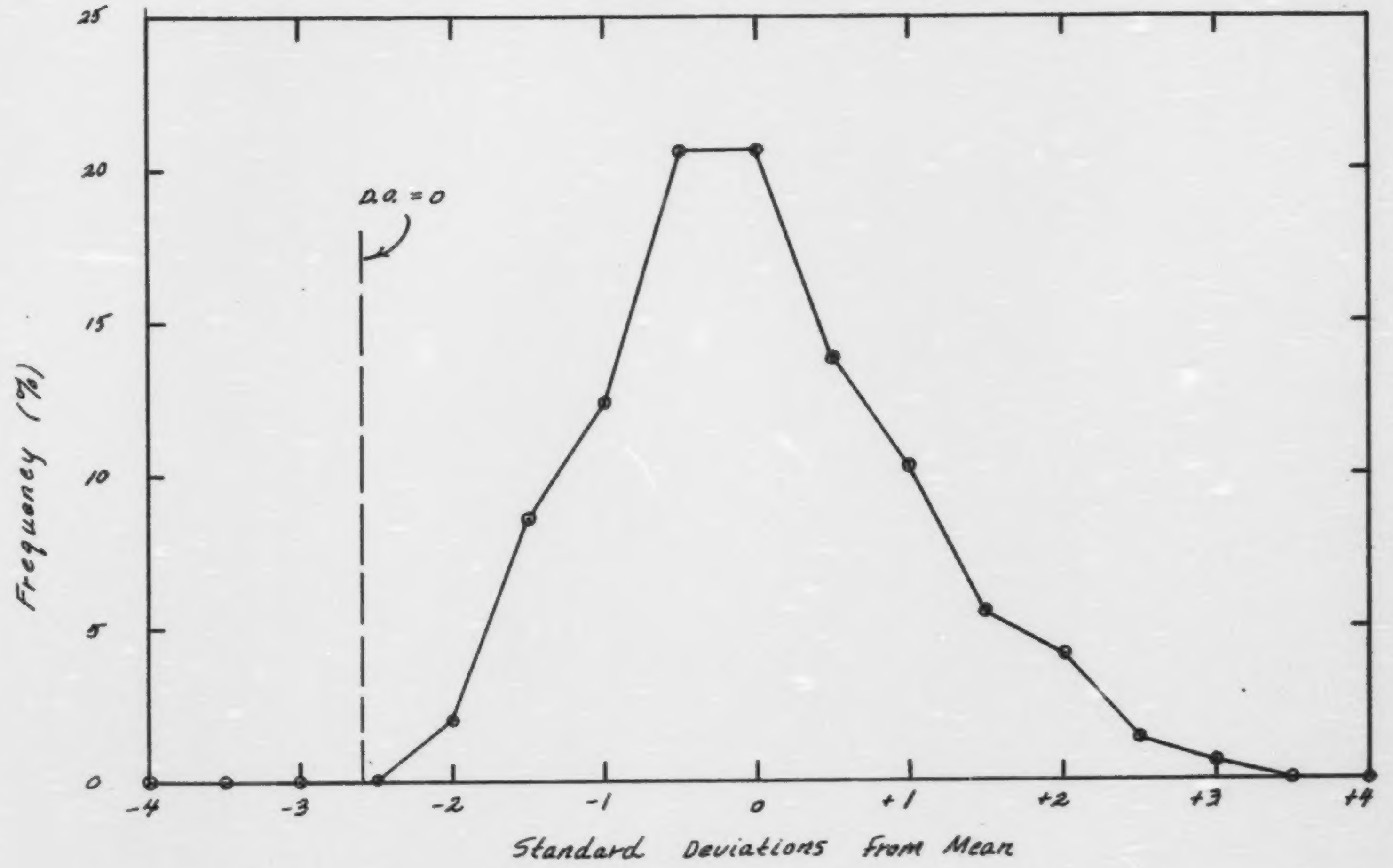


Figure 40
D.O. Frequency Distribution at Station 5

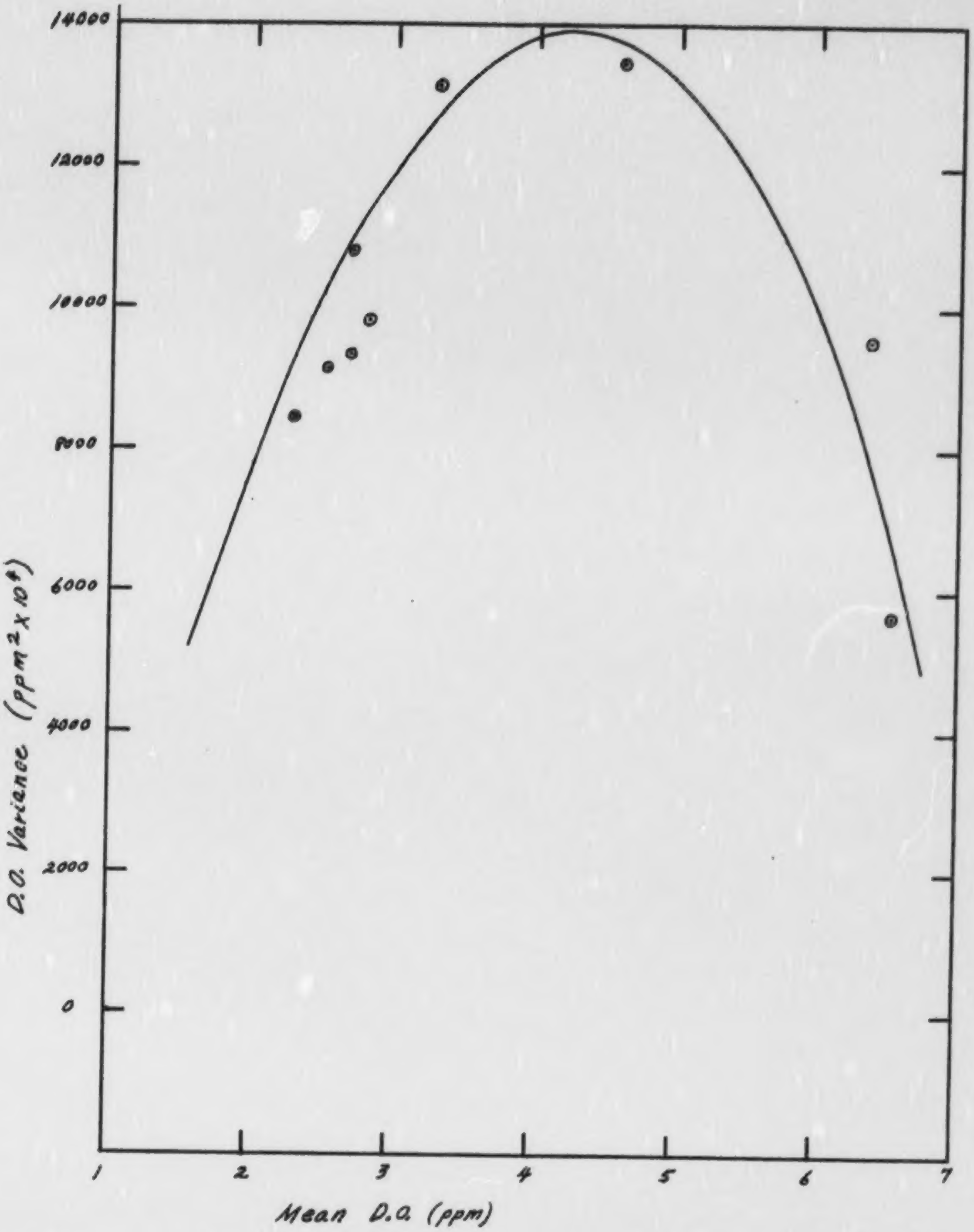


Figure 41
D.O. Variance as a Function of Mean D.O.

It is important to examine just how frequently extremely low D.O.'s do occur. For this purpose the frequency of occurrence of very low D.O.'s in the sampling records was determined. It was found that the probabilities of finding D.O.'s more than 1.6 standard deviations below the mean were very low. These results are presented in Table XIII.

Table XIII

Probability of Occurrence of Extremely Low D.O.

Station	Probability*
0	0.0
1	-
2	-
3	.05
4	.04
5	.03
6	.03
7	.03
8	.03

*Probability of the occurrence of a D.O. value more than 1.6 standard deviations below the mean in the field survey sampling records.

This means that a Station 3 (mean D.O. = 4.60 ppm) it would be expected that 95 percent of all samples taken during a similar flow period would be above 2.7 ppm. If these results are generalized to a station having a minimum mean D.O. of 4.00 ppm and a variance of about 1.3, 95 percent of all samples taken when the D.O. was at its minimum mean value would lie above 2.1 ppm.

In summary, it may be stated that these results show: (1) the total variance of a D.O. record depends on the mean D.O. rather than the physical characteristics of the station; (2) the highest variances are associated with mean D.O.'s of about 50-percent saturation; (3) the occurrence of extremely low D.O.'s is limited by the tendency of the frequency distributions to skew toward higher values; and (4) the occurrence of D.O.'s more than 1.6 standard deviations below the mean is highly improbable.

RESPONSE OF DISSOLVED OXYGEN TO SUNLIGHT

The response of the D.O. records to the variation in sunlight has been presented in Table XI. The increasing importance proceeding downstream of diurnal fluctuations and longer period variations is quite obvious. It seems likely that the diurnal variations are due to the differences in algal oxygen production and consumption in the daytime and at night, while the long-period effects might result from the increases and decreases in algal populations as they respond to changes in the environment. It might be further indicated that the algal population density might depend on the concentrations of nutrient material in the system.

The total response of D.O. to sunlight may be considered rather than the responses of individual frequencies; this is done by using the sum of the responses of the individual frequency bands. In this way the amount of the total variance which is due to sunlight can be examined. Figure 42 is the result of plotting the total D.O. response caused by sunlight as a function of the mean BOD at each station. The point representing Station 0 is regarded

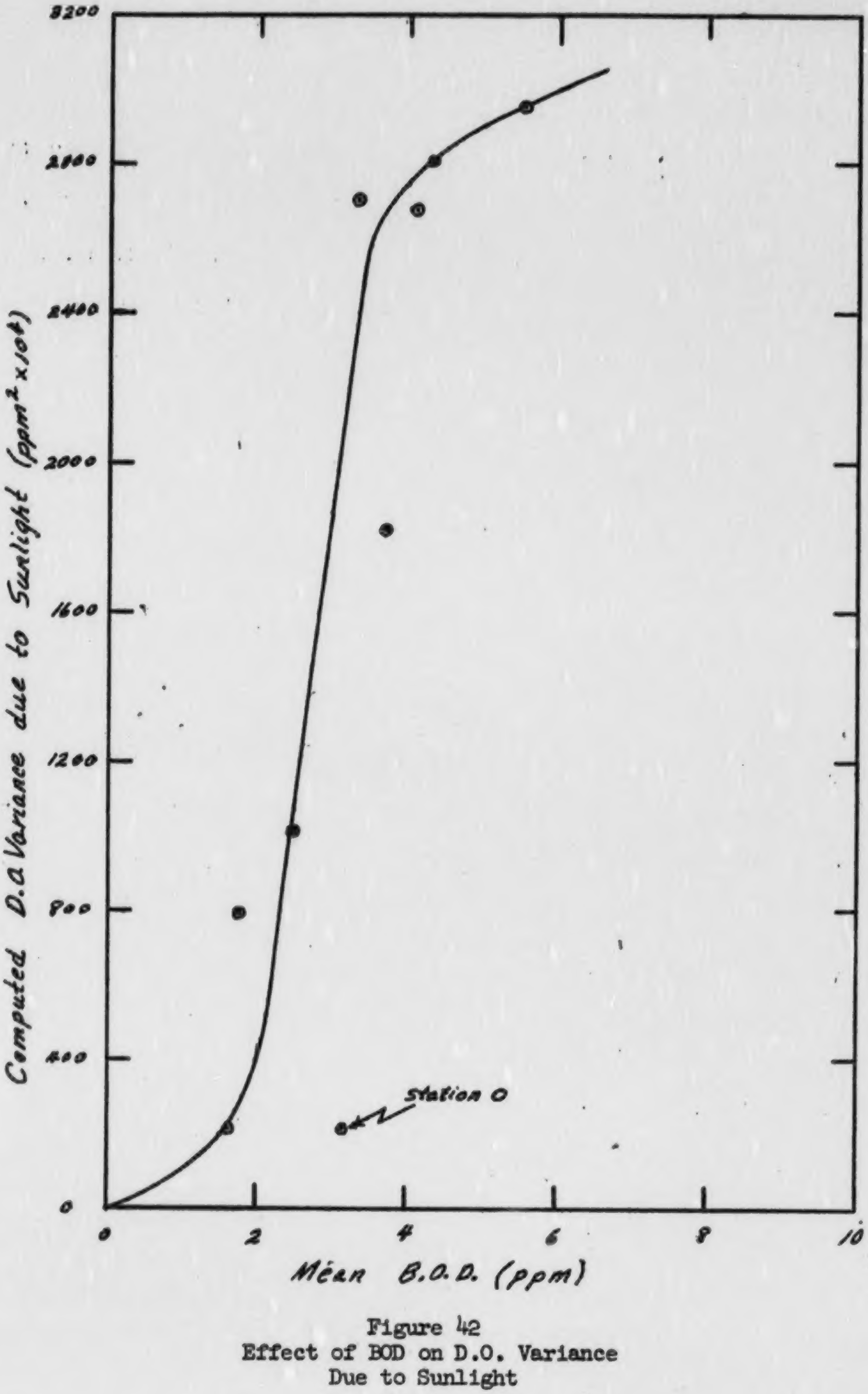


Figure 42
Effect of BOD on D.O. Variance
Due to Sunlight

as anomalous because of the extremely high turbidities prevailing in the Anacostia River. The mean value of turbidity at Station 0 was more than twice the values obtained at the other stations.

The sigmoid curve sketched in Figure 42 has been based on the assumption that the changes in D.O. response are the results of changes in algal population, and that the algal population depends directly upon the supply of nutrients as represented by the BOD. This type of curve is generally typical of the response of a population to a favorable environment. A straight line could be fitted to these data, but the sigmoid curve is more representative of the indicated mechanism. These results have demonstrated one aspect of the nonlinearity of the system; that is, the stream BOD affects the sunlight response. This effect is of considerable importance in estimating the waste assimilation capacity of the system, since the supply of nutrients from BOD could become large enough to dominate the D.O. regime.

It might be noted also that the algal population, hence the D.O. response to sunlight, affects the stream BOD. This result is in part an artifact of the BOD determination itself: the river water samples are placed in a dark incubator for 5 days. This means that much, if not all, of the algal population dies and decomposes, thus adding to the oxygen demand. The sunlight-algae-BOD-D.O. system might be represented schematically as in Figure 13.

In order to use the sunlight and stream BOD as separate primary drivers, it is desirable to determine the extent of the interaction between them and form some basis for eliminating any such interaction from the total D.O. response to sunlight or to BOD. The total response of BOD to sunlight was computed from the solor radiation-BOD cross-spectra for each station. These results are presented in Table XIV. Since it can be assumed that the stream

Table XIV

Response of Stream BOD to Sunlight

Station	Total BOD Variance	BOD Response to Sunlight Variance	Fraction of BOD Affected	BOD Variance Unaffected
0	.9560	0.169	0.177	0.787
1	.2940	0.0289	0.098	0.265
2	.3710	0.0575	0.155	0.313
3	.5890	0.0887	0.151	0.500
4	1.1200	0.129	0.115	0.991
5	1.1400	0.235	0.206	0.905
6	1.860	0.274	0.147	1.59
7	1.840	0.354	0.192	1.49
8	1.920	0.240	0.125	1.68

BOD does not affect solar radiation, the effect of sunlight on the D.O. response to BOD can be eliminated simply by subtracting from the D.O. response to BOD that fraction which can be attributed to sunlight in the manner just described. The stream BOD can then be regarded as a primary dirver acting independently of the sunlight.

The use of the D.O. response derived directly from the stream D.O.-solar radiation cross-spectra has certain great advantages over attempting to derive a D.O. response factor by using plankton counts, temperature, and stream BOD separately. For example, when the water temperature is highest the oxygen saturation value is lowest. This, however, might also be the time when algal oxygen production is highest, so that these two effects would tend to balance each other. It can be seen, therefore, that to follow the sunlight-D.O. system through the individual members of the chain would require a detailed knowledge of the amounts of interaction and the periods involved. While the direct computation of stream D.O. response to sunlight does not provide any direct knowledge of the internal workings of this system, it does indicate the over-all result; fortunately, in this case, that is all that is necessary.

RESPONSE OF STREAM D.O. TO STREAM BOD AND WASTE DISCHARGES

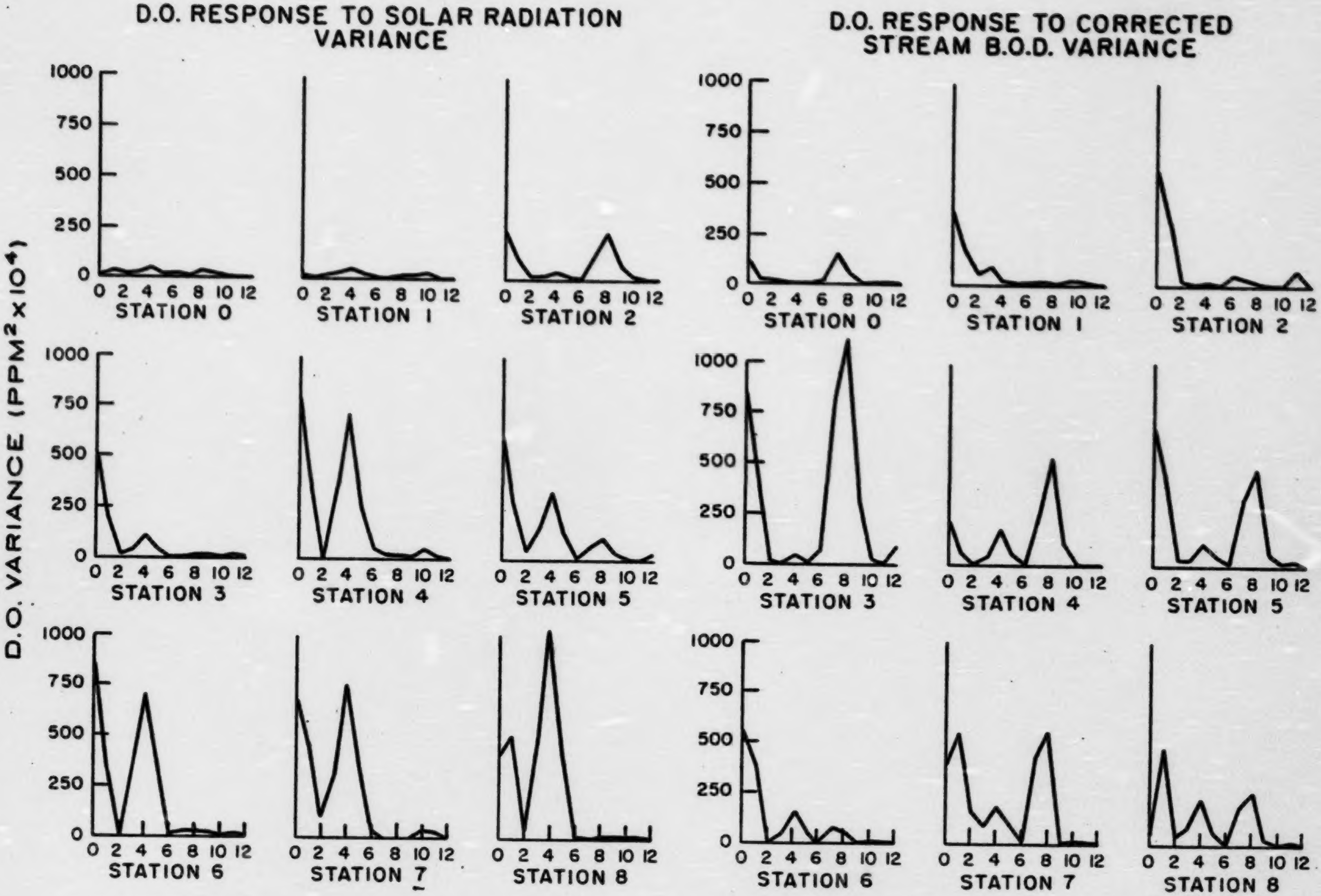
By using the approach given in the preceding section, the response of BOD to sunlight can be eliminated from the total BOD variance. This "corrected" BOD variance is then used to calculate the D.O. response to stream BOD. The D.O. responses calculated in this way for each station are presented in Table XV and in Figure 43. The computed spectra exhibit significant changes from station to station. These results can be related to the spectra of waste volume discharged and to the river-tide.

The waste volume discharges are all dominated by a strong diurnal fluctuation, while the tidal river motion is dominated almost entirely by a semidiurnal effect. These conditions might be expected to have these effects on the stream BOD spectra: within the limits of a tidal excursion from an outfall, there may be a noticeable diurnal effect as well as a pronounced semidiurnal component. The relative magnitudes of these two components would depend upon the size relationships of the waste discharge, receiving water volume, and stream BOD already present and upon the intensity of mixing in the receiving medium. Outside the limits of a tidal excursion from a major

Table XV

Stream D.O. Response to Stream BOD
Corrected for the Effect of Sunlight

Station Band Number	0	1	2	3	4	5	6	7	8
0	104	362	580	80.6	231	718	567	376	0.120
1	20.6	158	339	466	61.7	437	376	550	477
2	17.6	53.9	24.0	11.2	6.81	26.5	7.98	165	40.4
3	2.24	65.6	11.2	6.56	37.7	29.1	47.6	86.5	88.2
4	3.22	14.3	21.0	40.2	178	110	155	176	229
5	1.12	9.54	0.569	10.4	50.5	42.6	59.7	92.9	63.0
6	20.6	10.0	56.0	64.0	25.3	20.7	0.878	7.21	1.51
7	149	17.6	35.0	821	269	341	75.4	422	192
8	44.8	0.871	18.0	1090	527	488	59.5	567	273
9	3.75	22.8	3.67	303	101	61.9	2.77	12.7	31.0
10	9.22	18.9	0.310	24.6	0.316	19.8	12.2	19.5	1.58
11	11.3	5.91	75.7	8.40	0.772	29.3	14.7	12.9	15.4
12	1.58	1.83	24.2	85.9	0.072	8.19	5.34	0.00	7.81
Total	389	741	1190	3010	1490	2330	1380	2490	1420

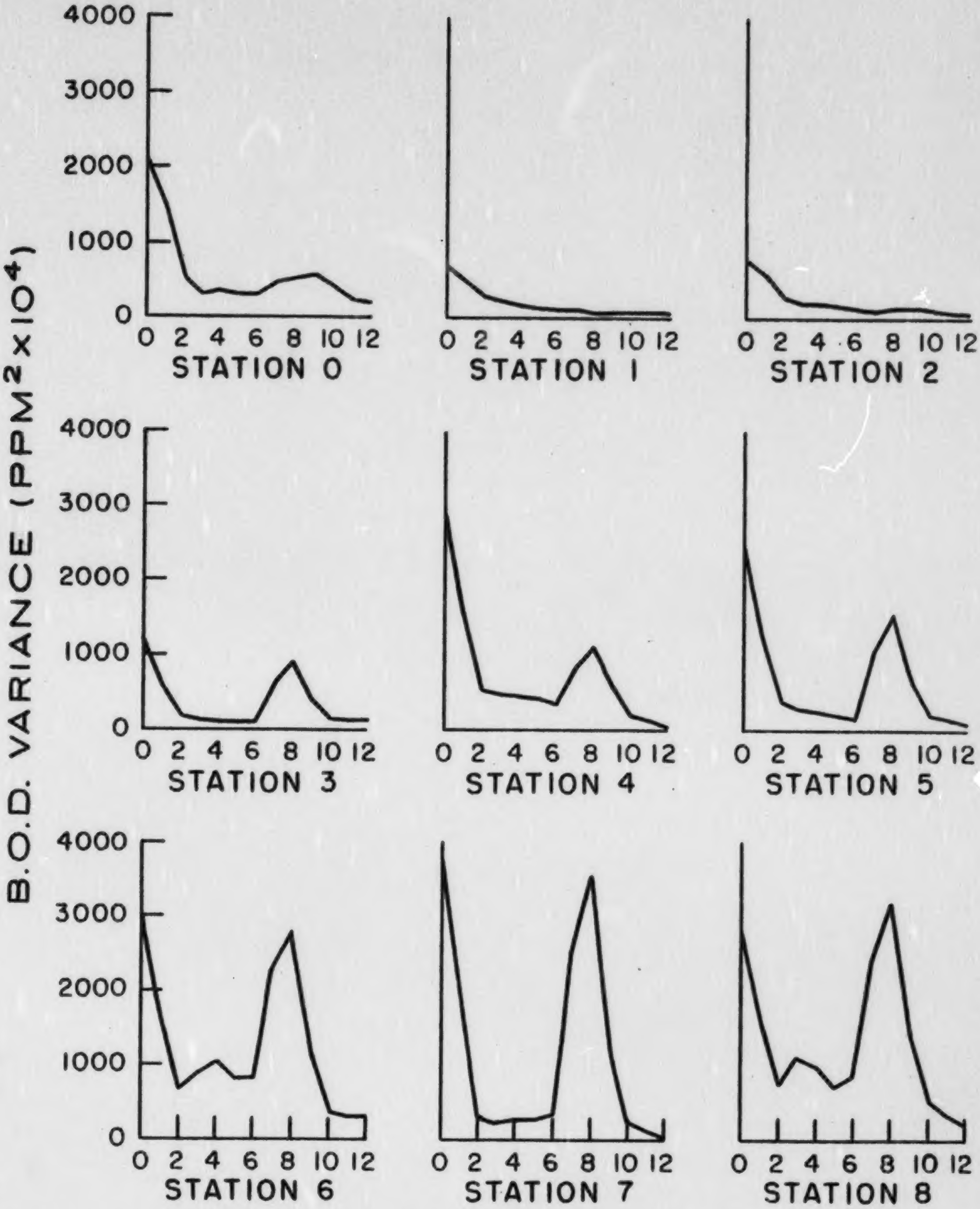


STREAM D.O. RESPONSE TO SUNLIGHT AND CORRECTED STREAM B.O.D.
FIGURE 43

outfall, the stream BOD fluctuations would be dominated by the semidiurnal effect to the practical exclusion of diurnal effects. The magnitude of the semidiurnal effect observed at any station would depend on the longitudinal BOD gradient weighted by the tidal excursion; this effect might be regarded as a measure of the longitudinal turbulent mixing.

The corrected stream BOD spectra are presented in Figure 44. It is informative to compare these spectra with the computed response spectra of D.O. to stream BOD The BOD spectra for Stations 3 to 8 exhibit dominant long-period and seimdiurnal effects; while the diurnal effect is noticeable at Station 6, 8, and possibly 4, it is quite suppressed. From these spectra it might be deduced that the volume of waste discharged is quite small compared to the volume of the river into which it is discharge; the strength of the semidiurnal peaks would indicate the longitudinal BOD change is fairly small in the waters which flow past Stations 3, 4, and 5 during a tidal cycle, while the changes in the waters flowing past Stations 7 and 8 are rather large. Station 6 shows an intermediate condition. Figure 45 shows the volumes of water in the system at mean high water and at mean low water. The head of tidewater is assumed to be at the Three Sisters Island. This figure may be used to obtain a crude idea of the length of a tidal excursion in this reach of the system. For example, water opposite the Blue Plains outfall (Station 6) at high tide was about halfway between Stations 7 and 8 at low tide, while water at Station 6 at low tide lies between Stations 4 and 5 at high tide. It should be clearly understood that this type of estimate is quite crude and is based only on volume displacement. Not only are there large inherent errors in the volume measurements, but also no account is taken of the current structure of the system of the effect of river discharge. This figure is presented to give only some crude idea of what the tidal excursion might be like. It can be seen that the water flowing by Stations 3, 4, and 5 during a tidal period comes primarily from the region between Station 7 and a short distance above Station 3; some water would also come from the Anacostia River. The mean BOD's for these stations are given in Table V. The bulk of the water involved would be represented by the mean BOD values at Stations 0, 4, 5, 6, and 7. These values are 3.15, 3.34, 3.73, 4.10, and 4.30, respectively. Only a small amount of the water involved would be represented by the mean BOD of 2.44 at Station 3. It may be also noted that the BOD's from Station 6 to 8 would begin to show the effects of larger tidal excursions, which would appear as a larger BOD change in the water moving past the station. (If the longitudinal BOD changes in the tidal excursion at each station were weighted according to the length of the tidal excursion, the results might provide some measure of the turbulent mixing processes.)

These results and the postulated mechanism may now be considered in comparison with the D.O. response spectra. It is immediately evident that the D.O. response to the diurnal BOD fluctuations is proportionately greater than to the semidiurnal fluctuations; in some cases the diurnal effects are about the same magnitude as the semidiurnal, as at Stations 6 and 8. Since the diurnal BOD component is regarded as that part of the total stream BOD which has been most recently discharged from the treatment plants, the large D.O. response to this component can be regarded as representative of the



CORRECTED STREAM B.O.D. SPECTRA

FIGURE 44

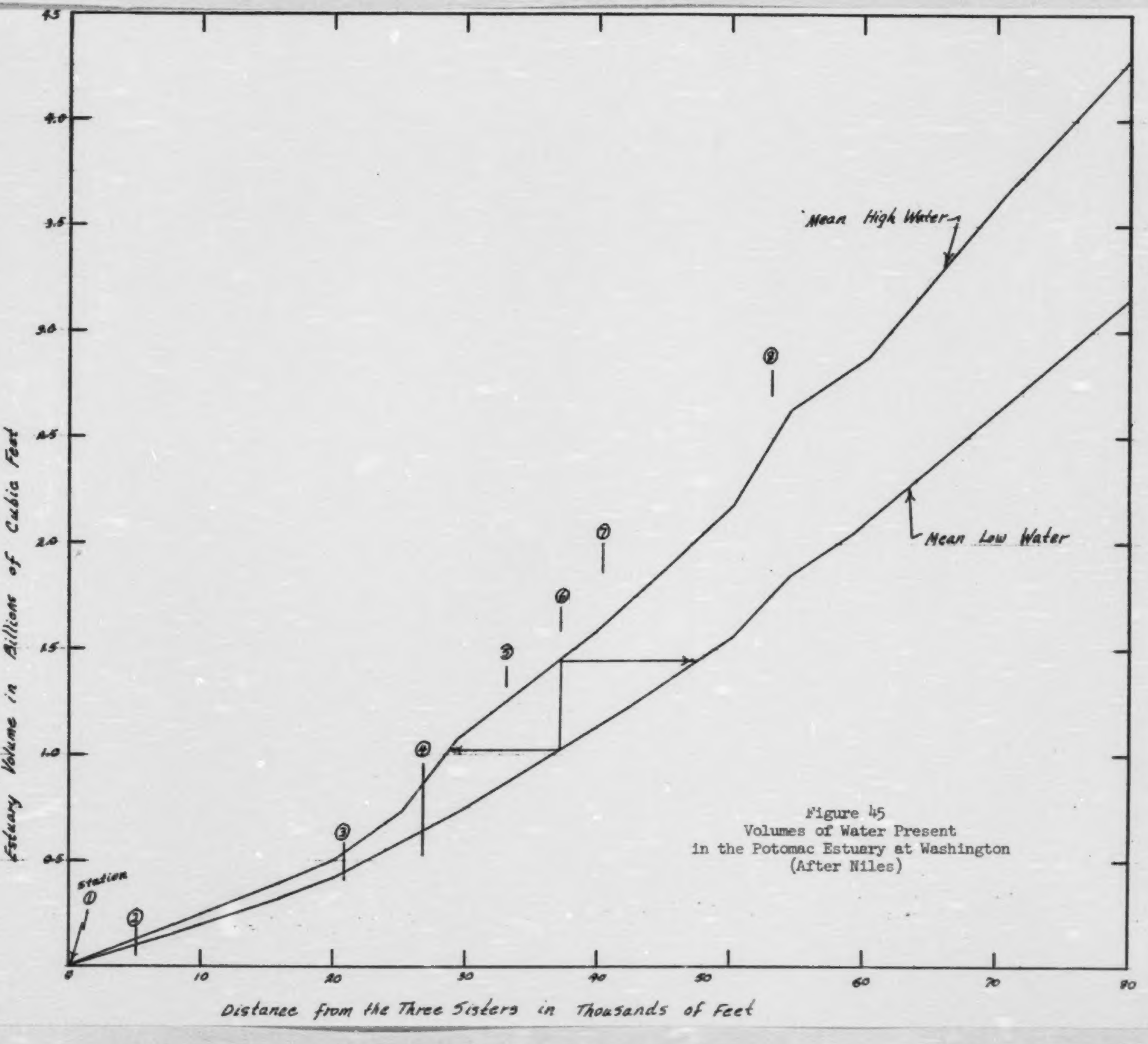


Figure 45
Volumes of Water Present
in the Potomac Estuary at Washington
(After Niles)

rapid biochemical utilization of waste materials well broken down by the treatment processes, while the gradual assimilation of the remaining materials is reflected in the long-period and semidiurnal effects.

For estimation of the waste assimilation capacity it is necessary to calculate the total D.O. response to the stream BOD. This is done by dividing the total D.O. response to BOD by the total corrected BOD variance at each station; the square root of this quotient is the desired factor. The results of this calculation are presented in Table XVI. These results are consistent with the observed D.O. frequency distributions. BOD changes have the greatest effect when the mean D.O. is about 50 percent of saturation. Slight changes in the BOD also have a larger effect at the less polluted stations than at those having higher degrees of pollution.

Table XVI

Total Response of D.O. to Stream BOD

Station	$\frac{\text{ppm D.O.}}{\text{ppm BOD}}$
0	.222
1	.529
2	.615
3	.776
4	.387
5	.508
6	.295
7	.409
8	.287

It is necessary to relate the stream BOD to the waste discharged. Time series of the quantities of wastes discharged were not measured, so it is not possible to evaluate the effects of the waste discharges on the BOD records. The data available for the waste loads discharged are presented in Table IV. The pertinent statistics calculated from these data are:

W = mean waste load discharged = 86,450 pounds per day of BOD_5

S^2 = variance of the mean waste load = 228.492×10^6

The response of the stream BOD to the waste discharge can be estimated by dividing the mean stream BOD at each station by the mean waste discharge. The use of this procedure is to assume that all of the stream BOD is due to the waste discharge; this would lead to an underestimate of the waste assimilation capacity, thus producing a conservative result.

While the selection of any background BOD level is necessarily arbitrary, it is desirable that some allowance be made for such a load. An arbitrary background load of 10,000 pounds per day of BOD_5 has therefore been selected. This is equivalent to a BOD of 0.93 ppm in the mean river discharge of 2,000 cfs. Since the mean BOD at Station 1, the farthest station upstream, was 1.62, this value seems fairly reasonable. This assumed background load was added to the mean daily waste load to determine the total waste load.

The spectral results can be used to obtain a check of these values. The waste discharges as presented in Table IV are daily means; that is, all fluctuations of periods less than 24 hours have been averaged out. The variance calculated from these data would correspond to the long-period variance of the spectra. The principles involving the Nyquist frequency would also apply here.

The 24-hour sampling interval would permit the resolution of a 48-hour cycle, but only for a very long record. The extremely short record available here would show only the effects of periods much longer than this. To obtain the actual long-period variance from the stream BOD record, it was decided to reverse the smoothing procedure and to use as the long-period spectral estimate the estimate for Spectral Band 0 plus one half the estimate for Spectral Band 1.

The results of this calculation and the alternate method for computation of the response of the stream BOD to waste discharge are presented in Table XVII.

Table XVII

Comparison of Methods Used for Computation of the Response of Stream BOD to Waste Discharge

Station	$\frac{\text{Mean BOD (ppm)}}{\text{W (lbs)}}$	L = Long-period Spectral Estimate	$\sqrt{L/S^2}$
0	3.27×10^{-5}	$2{,}890 \times 10^{-4}$	3.56×10^{-5}
1	1.68×10^{-5}	952×10^{-4}	2.04×10^{-5}
2	1.86×10^{-5}	$1{,}100 \times 10^{-4}$	2.19×10^{-5}
3	2.53×10^{-5}	$1{,}530 \times 10^{-4}$	2.58×10^{-5}
4	3.46×10^{-5}	$3{,}760 \times 10^{-4}$	4.06×10^{-5}
5	3.87×10^{-5}	$3{,}270 \times 10^{-4}$	3.79×10^{-5}
6	4.25×10^{-5}	$3{,}890 \times 10^{-4}$	4.13×10^{-5}
7	4.46×10^{-5}	$4{,}840 \times 10^{-4}$	4.60×10^{-5}
8	5.71×10^{-5}	$3{,}690 \times 10^{-4}$	4.02×10^{-5}

The agreement of the two methods is fairly good except in the case of Station 8. The values used for the subsequent calculations of waste assimilation capacity are those obtained by the division of the mean values (column 2). These values are based on 144 degrees of freedom and should be more stable than the individual spectral estimates, which are based on 23 degrees of freedom.

RESPONSE OF STREAM D.O. TO RIVER-TIDE

The combination of river discharge and tidal action affects the D.O. records in three major ways: (1) there is an advection of D.O. into the system with the river water; (2) there is a movement of D.O. already present in the water back and forth within the system; (3) there is a transport of D.O. through the air-water interface. The advective motion of oxygen within the system is due primarily to the tidal action, although the river discharge should introduce some perturbation into this process. The surface reaeration results from the interaction of the tide and river discharge. This interaction takes the form of changes in the turbulent eddy structure of the system; an increase in river discharge would bring about an increase in turbulent mixing, thus exposing more water at the interface per unit time and resulting in greater diffusion of oxygen into the water. This mechanism is distinctly nonlinear--changes in the turbulent structure would require transfers of energy among frequencies.

The response of tidal height at four points within the system to the river discharge[*] is presented in Table XVIII. This response for the Bellevue tide gage is pictured in Figure 46. The responses elsewhere in the system are similar, as may be seen in Table XVIII. The dominant response of the tide height is at the semidiurnal frequency. It may also be seen in Figure 46 that there are small but significant responses in the vicinity of the harmonics of the semidiurnal period; namely, at 6- and 3-hour periods. A comparison of this figure with the river discharge spectrum shows that there has been a transfer of energy from the dominantly long-period river discharge to the dominantly short-period tidal flow. The existence of a nonlinear interaction between tidal action and river discharge has been demonstrated, and the extent of this interaction is related to the tide gage records. Included in Table XVIII are the phase lags of the semidiurnal component of the tide gage response to river discharge. These may be interpreted as the number of hours between the measurement of a discharge at Little Falls and its perturbation of the tidal system. The internal agreement of these phase lags shows that the river discharge effects are felt practically simultaneously throughout

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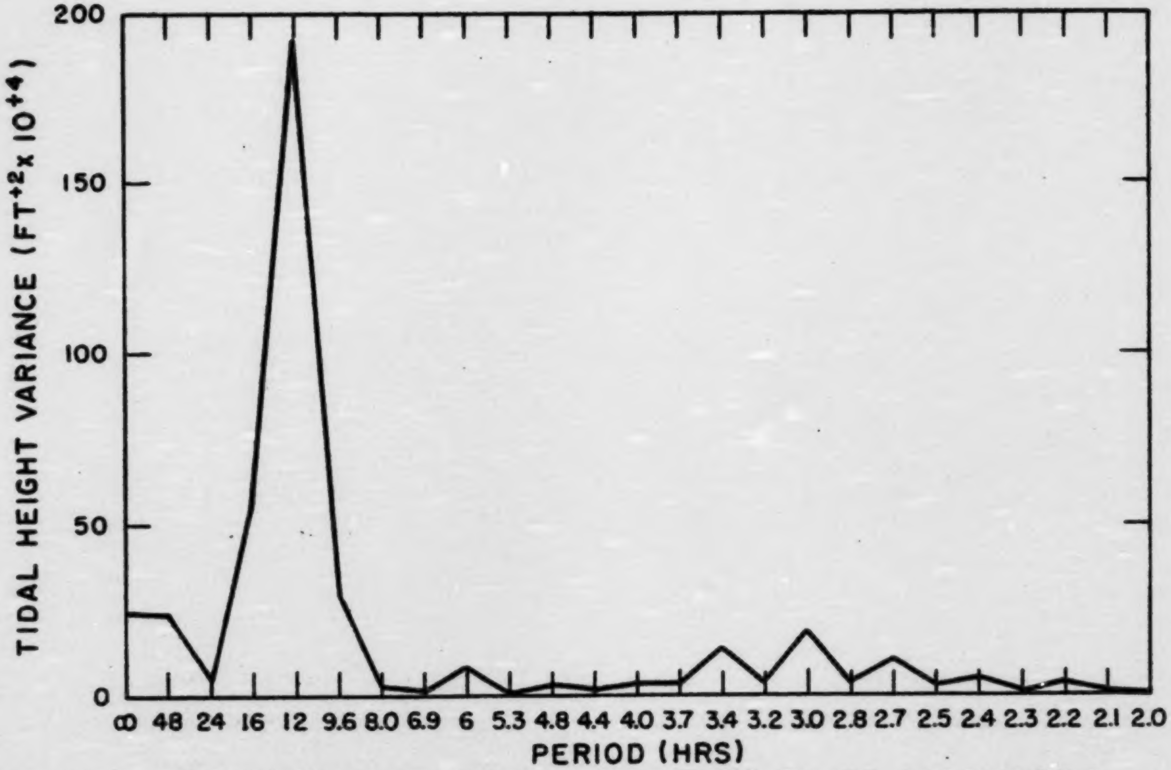
[*] Since continuous records were available for these parameters, the records were sampled at intervals corresponding to one (1) hour, and the cross-spectra were run at 24 lags. This permitted greater resolution of the frequency bands, though at some cost in confidence limits. For the cross-spectra of each of these records with D.O., BOD, and temperature, the records were sampled at 4-hour intervals to correspond to the sampling interval in the latter parameters.

Table XVIII

Response of Tide Gage Records to River Discharge Variance

Period (Hrs)	Tide Gage Variance (ft^2 x 10^4)			
	Wisconsin Avenue	Gravelly Point	Bellevue	Alexandria
∞	25.3	12.6	24.8	25.8
48	23.6	14.5	23.5	21.1
24	4.19	3.13	4.78	2.30
16	77.5	87.2	57.1	84.2
12	200	272	192	176
9.6	25.0	38.4	31.1	19.3
8.0	6.66	3.66	3.14	4.67
6.9	0.794	0.0525	1.22	0.230
6.0	4.76	1.67	8.62	1.38
5.3	3.04	1.48	0.319	1.39
4.8	2.53	1.32	3.21	2.66
4.4	3.19	1.57	1.87	2.56
4.0	10.0	4.77	4.74	5.29
3.7	2.13	1.32	3.52	2.98
3.4	8.91	10.6	14.4	9.43
3.2	2.62	1.78	4.13	2.72
3.0	14.9	10.5	19.0	13.1
2.8	3.74	1.50	3.72	2.21
2.7	11.0	4.34	10.8	7.37
2.5	2.28	0.882	3.00	1.70
2.4	5.49	2.72	5.54	3.55
2.3	1.51	0.885	2.08	1.13
2.2	3.53	2.06	4.53	2.47
2.1	1.12	0.477	1.46	0.531
2.0	0.682	0.258	0.990	0.301
Phase Lag (Hrs)	9.5	9.3	9.3	9.3



RESPONSE OF TIDAL HEIGHT TO RIVER DISCHARGE
AT BELLEVUE

FIGURE 46

this part of the system; this indicates that an energy transfer process is a more probable mechanism for the observed result than is the physical advection of the river discharge to the tide gage locations.*

The difference in character between the river discharge records and the tide gage records is worthy of some consideration. The tide gage records represent the effect within the system of the interaction between river discharge and tidal action; that is, the perturbation of the tidal regime by the river discharge, and the turbulent mixing and reaeration which can be expected to result from this. The river discharge records, on the other hand, represent a quantity of water entering the estuary--a quantity which is being measured outside the system itself. This means that the stream D.O. response to river discharge would reflect changes in the quantity of oxygen being advected into the system by changes in the river discharge. This response would also reflect changes in the stream D.O. related to the changes in the quantity of heat being advected into the system by the river discharge; that is, the temperature changes related to the changes in river discharge.

It is informative to compare the response of stream D.O. to river discharge with the response of temperature at the sampling stations to river discharge. The former response is given in Table XI and the latter is presented in Table XIX. Table XI shows that the stream D.O. response to temperature is composed of significant long-period diurnal, and semidiurnal effects at nearly all stations. Table XIX shows that the response of estuary temperature to the

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*If this phase lag is regarded as the time of water travel between Little Falls and the head of tidewater at the Three Sisters, then the average velocity over this distance of roughly 4 miles is about 0.6 feet per second. The average grade over this reach of the river is about 0.2 percent.

Table XIX

Response of Water Temperature Variance to River Discharge Variance

	Water Temperature Response (^{o}C. x 10^{2})								
Station	0	1	2	3	4	5	6	7	8
Band Number									
0	136	84.9	91.6	91.6	86.2	78.4	73.5	73.5	50.71
1	57.0	36.4	39.3	37.0	32.9	30.4	28.3	28.5	19.75
2	1.29	0.531	0.420	0.282	0.107	0.114	0.071	0.130	0.061
3	0.165	0.180	0.078	0.071	0.099	0.030	0.045	0.022	0.023
4	0.836	0.466	0.661	0.209	0.397	0.198	0.335	0.265	0.363
5	0.302	0.0033	0.0013	0.0060	0.071	0.043	0.0019	0.0041	0.027
6	0.278	0.163	0.168	0.0102	0.021	0.011	0.0031	0.0015	0.001
7	0.051	0.084	0.047	0.0130	0.017	0.0012	0.0099	0.0072	0.079
8	0.032	0.223	0.236	0.427	0.064	0.129	0.051	0.040	0.004
9	0.178	0.115	0.019	0.0073	0.021	0.030	0.053	0.045	0.026
10	0.0081	0.119	0.104	0.025	0.026	0.0035	0.018	0.047	0.111
11	0.0758	0.025	0.0056	0.0071	0.0067	0.010	0.0064	0.0040	0.009
12	0.006	0.0076	0.0091	0.0098	0.018	0.016	0.0003	0.0033	0.002
Total	196	123	133	130	120	109	102	103	71.2
Phase Lags	Long-period effects out of phase with discharge.								

river discharge is almost entirely long-period. It is also indicated that these long-period effects are out of phase with the river discharge; in other words, an increase in river flow causes a decrease in temperature, at least for this time of year. These results can be converted to temperature change per 1,000 cfs by dividing the D.O. response variance by the river discharge variance and taking the square root of the quotient. These results can then be compared with observed temperature changes during the survey period. This is done in Table XX.

Table XX

Comparison of Computed Response of Water Temperature Change to River Discharge with Observed Response

Station	Computed Response (°C./1,000 cfs)	Total Computed Response (°C.)	Observed D.O. Change (°C.)	Observed ÷ Computed	Number of Days to Reach Computed Response
0	1.81	3.4	2.6	0.76	2.6
1	1.44	2.7	1.8	0.67	3.0
2	1.49	2.8	1.9	0.68	3.0
3	1.48	2.8	1.5	0.54	3.7
4	1.42	2.6	0.9	0.35	5.7
5	1.35	2.5	0.8	0.32	6.3
6	1.31	2.4	0.5	0.21	9.5
7	1.31	2.4	0.4	0.17	11.8
8	1.09	2.0	0.3	0.15	13.3

The period chosen for comparison is August 7 through 9. During this period the river discharge rose from 1,570 cfs 3,430 cfs (daily mean, a total change of 1,860 cfs. There was also a change from a predominantly cloudy regime to clear skies, which would tend to counteract the effects of the river discharge on temperature. The observed temperature changes are the difference of the daily mean values presented in Table VI for August 7 and 9. The results presented in Table XX show that the observed temperature changes are not as high as the computed values. They also show a systematic decrease down the river in the ratio of observed to computed values. Since the change in estuary temperature is brought about by the transport of colder water through the system, and since this process can be expected to be gradual, these results seem quite consistent. Since the discharge did not remain high for a period long enough to approach steady-state conditions, the full value of the computed response would not be expected for the example used here.

River discharge cannot be expected to have this same effect on estuary temperature at all seasons of the year. This response as derived from the stream data is, however, expected to be typical with low flows in late summer conditions.

The D.O. response of the estuary to the river discharge can be related to the temperature response. The temperature response of 1.4°C. decrease per 1,000 cfs increase would amount ot an increase in quantity of D.O. entering the system of 1,130 pounds per day for a 1,000 cfs increase in river discharge. The D.O. response to river discharge as given in Table XI can be converted to ppm D.O. change per 1,000 cfs as was done with the temperature response. The results of this computation are presented in Table XXI. The mean D.O. response

Table XXI

Advective D.O. Response of
Stream Stations to River Discharge

Station	Advective D.O. Response Per 1,000 cfs (ppm)	Total Oxygen Required (lbs.)	Days of 1,000 cfs Flow Required
0	.030	-	-
1	.066	300	.3
2	.083	980	.9
3	.067	2,000	1.8
4	.077	3,100	2.7
5	.064	5,000	4.4
6	.067	5,200	4.6
7	.060	6,000	5.3
8	.076	9,900	8.7

for all stations except Station 0 is 0.07 ppm D.O. per 1,000 cfs. By using the mean volume of the system above each station as obtained from Figure 45, the total pounds of oxygen and the number of days of 1,000 cfs additional flow to achieve a uniform increase of 0.07 ppm D.O. throughout the system above each station can be calculated. The results of these computations are also presented in Table XXI. The days of flow required to achieve the computed D.O. response may be compared with the number of days required to reach the computed temperature response as presented in Table XX. It may be noted that the days of flow required for the computed D.O response are consistently less than the number of days estimated for the temperature response. This is obviously partially because no allowance has been made in Table XXI for the removal of D.O. from the system by advection downstream; it might be noted that an 11 percent loss of the advected D.O. downstream from Station 8 each day would be sufficient to bring the times into agreement.

This discussion has indicated that the interpretation of stream D.O. response to river discharge as changes in D.O. advection related to changes in temperature of the incoming water is consistent with the observed results.

The over-all stream D.O. response to the river-tide variance can be computed in two ways. Both ways require the postulated independence of the primary drivers: solar radiation, corrected stream BOD, and river-tide parameters. First, the sum of stream D.O. response to corrected stream BOD and solar radiation can be subtracted from the total D.O. response at each station. This estimate will be somewhat in error by the amount that river discharge affects estuary temperature (Figure 13). A correction can be made for this error. The results presented in Table XIX show that the effects of river discharge are over 98 percent long-period (Spectral Bands 0 and 1). The long-period D.O. response to temperature can therefore be attributed to changes in the river-tide regime, while the remainder of the D.O. response to temperature can be attributed to the effects of solar radiation. These effects have already been included with other sunlight effects in the total response of stream D.O. to sunlight, so no correction for the interaction of the effects of sunlight and river discharge is possible in this method of calculation without detailed knowledge of the internal workings of the system. The stream D.O. response to river discharge calculated in this manner is presented in Table XXII. Second, the total D.O. response to river-tide may be calculated by adding the responses directly associated with river discharge and the tidal height as perturbed by the river discharge. In using this approach it is necessary to consider the relationship of temperature in the estuary to the river discharge. The stream D.O. response to river discharge has been attributed to the advection of oxygen into the system by the river flow, while the response of D.O. to the tidal height variance has been attributed to the perturbation of the turbulent regime by the river discharge. It is now necessary to consider what is the significance of the response of temperature in the estuary to variation in river discharge.

It must be emphasized that the results of the data analysis can only tell what actually happened during the survey period, not what might have happened on some theoretical basis. In evaluating predominantly short-period drivers and responses, it can be expected that the data exhibit the full system response to the drivers. With a predominantly long-period response the full response may or may not have been achieved in the experimental data. This has been illustrated in Table XX and the accompanying discussion, where there are considered the computed and observed temperature responses to an observed change in river discharge. It was noted in this discussion that the sustained high discharge of 3,430 cfs for 2 days was not sufficient to produce the full computed temperature change related to the change in river discharge. If the full temperature response is not achieved in such a case, it is reasonable to assume that the full D.O. response to temperature is also not developed. If this has been the case in the experimental records, then

Table XXII

Total Stream D.O. Response to River-Tide Obtained by Difference

Station	Stream D.O. Variance (ppm^2)				Total Stream D.O. Response (ppm/1000 cfs)
	Observed Total Response	Related to:			
		Sunlight Variance	Corrected Stream BOD Variance	River-Tide Variance (by difference)	
0	.842	.0216	.0389	.782	1.15
1	.568	.0219	.0741	.472	0.89
2	.958	.0798	.119	.759	1.13
3	1.35	.102	.301	.947	1.26
4	1.32	.270	.149	.901	1.23
5	1.08	.182	.233	.665	1.06
6	.934	.268	.138	.528	0.94
7	.915	.282	.249	.384	0.80
8	.984	.296	.142	.546	0.96
			Mean total Stream D.O. Response:	All Stations	1.05
				Stations 2-8	1.05

the cross-spectra of D.O. and river-tide will not show the full effects of this response, and the measured response of the stream D.O. to river-tide will be low by some factor which depends on the actual river discharge variance and the length of time required to develop the full D.O. effect of the river discharge.

The magnitude of this factor can be developed through an examination of the long-period responses of stream D.O. to stream temperature and of stream temperature to river discharge. The spectral results used in this examination and the results of the computations involved are presented in Table XXIII. The results presented in this table have been obtained in this manner:

Columns 2 and 3 - these are taken from Table XI.

Column 4 - Values in column 3 are divided by the variance of river discharge (.0373), the square root of the quotient is taken, and the value is divided by 4 which is the conversion from feet of gage height to cubic feet per second discharge for the range of discharges encountered in the field survey.

Column 5 - the values in column 2 are divided by the corresponding values in column 3, and one-fourth of the square root of this quotient is entered in column 5.

Column 6 - these values are the advective D.O. response values from Table XXI.

Column 7 - each value in column 6 is subtracted from the corresponding value in column 5.

Column 8 - each value in column 5 is divided by the corresponding value in column 4.

The difference between the observed and computed stream D.O. responses are the factors which should be added to the D.O. response to river-tide in order to obtain the total D.O. response to a continuous steady discharge.*

The total stream D.O. response to river-tide can now be calculated by adding the D.O. responses to river discharge variance, river-tide variance, converting the sum to ppm D.O. response per 1,000 cfs, and then adding to this the appropriate value from column 7 of Table XXIII. These results are presented in Table XXIV. Stream D.O. responses for Stations 0 and 1 are not calculated because the necessary cross-spectra were not run for Station 1, and because the observed long-period D.O. response to temperature is so small, the calculated difference between observed and computed D.O. is regarded as anomalous. Since this station is not on the main stem of the estuary, it may be expected that a continuous high discharge for a much longer period than occurred during the survey will be required to produce the full D.O. response.

The agreement between the results presented in Table XXII and those presented in Table XXIV is quite good, 1.05 in the former case and 0.96 in the latter for Stations 2 through 8. It seems reasonable to assume, therefore,

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*It is interesting to note that the mean of the computed D.O. response per degree Centigrade (column 8) for all stations except Station 0 is 0.16 ppm D.O. per degree Centigrade, which is in close agreement with the rate of change of D.O. saturation concentrations with temperature (0.15 ppm D.O. per degree Centigrade) as given in Standard Methods (10th edition) for the temperature range during the field study. If Station 0 is included in the sampling station mean, the agreement is better.

Table XXIII

Total Stream D.O. Response to River Discharge

Station	Stream D.O. Response to Temperature (ppm)^2	Temperature Response to River Discharge		Stream D.O. Response to River Discharge			
		(degrees C.)^2	$\frac{\text{degrees C.}}{\text{1000 cfs}}$	ppm/1000 cfs Computed	ppm/1000 cfs Observed	ppm/1000 cfs Difference	$\frac{\text{ppm}}{\text{degree C.}}$
0	.00054	1.93	1.80	.016	.030	-.014	.009
1	.0425	1.21	1.43	.187	.066	.121	.130
2	.0560	1.31	1.48	.207	.083	.124	.145
3	.0646	1.29	1.47	.224	.067	.157	.152
4	.0576	1.19	1.41	.220	.077	.143	.156
5	.0659	1.09	1.35	.246	.064	.182	.182
6	.0428	1.02	1.31	.205	.067	.138	.156
7	.0218	1.02	1.31	.146	.060	.086	.111
8	.0611	0.75	1.09	.294	.076	.218	.270

Table XXIV

Total Stream D.O. Response to River-Tide Obtained by Summation

Station	Stream D.O. Variance (ppm^2) Related to:			Total Stream D.O. Response (ppm/1000 cfs)	
	River Discharge Variance	River-Tide Variance	Total River-Tide Variance	Uncorrected	Corrected
0	.0144	.422	.436	0.86	-
1	.0692	-	-	-	-
2	.110	.0544	.164	0.53	0.65
3	.0724	.405	.477	0.90	1.06
4	.0938	.489	.583	0.99	1.13
5	.0654	.473	.538	0.95	1.13
6	.0708	.267	.338	0.75	0.89
7	.0568	.221	.278	0.68	0.77
8	.0917	.383	.475	0.89	1.11
	Stations 2-8	Mean Total	Stream D.O. Response		0.96

that the physical basis on which the spectral results were interpreted is reasonably valid. Further calculations in this report, the mean of these results, 1.01 ppm D.O. increase per 1,000 cfs discharge increase, will be used.

OXYGEN-SAG ANALYSIS

The results obtained through spectral analysis may be checked in a crude way by using the long-term BOD results obtained during the survey as the basis for a form of oxygen-sag analysis using the classical Streater-Phelps formulation. In differential form, the oxygen-sag equation, can be expressed as:

$$\frac{dD}{dt} = k_1L - k_2D$$

where:

$\frac{dD}{dt}$ = time rate of change of D.O. deficit,

L = amount of BOD remaining,

D = existing D.O. deficit,

k_1 = empirical constant identified as "deoxygenation rate constant," and

k_2 = empirical constant identified as "reaeration rate constant."

For a tidal system such as this one, it is convenient to use this formulation in its finite difference form:

$$\frac{\Delta D}{\Delta t} = k_1L - k_2D$$

During the survey eleven long-term BOD's were run on samples obtained at each of the sampling stations near Fort Washington and Marshall Hall. The data obtained from these determinations are presented in Table XXV. For the purposes of this analysis the value $k_1' = 0.10$ at 20°C. has been chosen as representative of the stream conditions during the survey. Figure 47 shows that this value is consistent with the oxygen depletions observed in the first days of the long-term BOD runs.*

From this value and the daily mean values of D.O., BOD, and temperature at the stream stations, the value of k_2 can be calculated for each station on each day of the survey. This has been done for Stations 4, 5, 6, and 7. These results are presented in Table XXVI and in Figure 48. The "ultimate" BOD, L, is calculated from the average of two daily means by dividing by 0.684. The daily mean D.O. values are converted to oxygen deficit by using the oxygen saturation value for each temperature; $\frac{\Delta D}{\Delta t}$ is the difference between successive values of the deficit, and D is the average of two successive values. K_2 may then be calculated using the finite difference form of the oxygen-sag equation. The successive results are then averaged to form the running daily mean for each day. The running means are the values presented in Figure 48.

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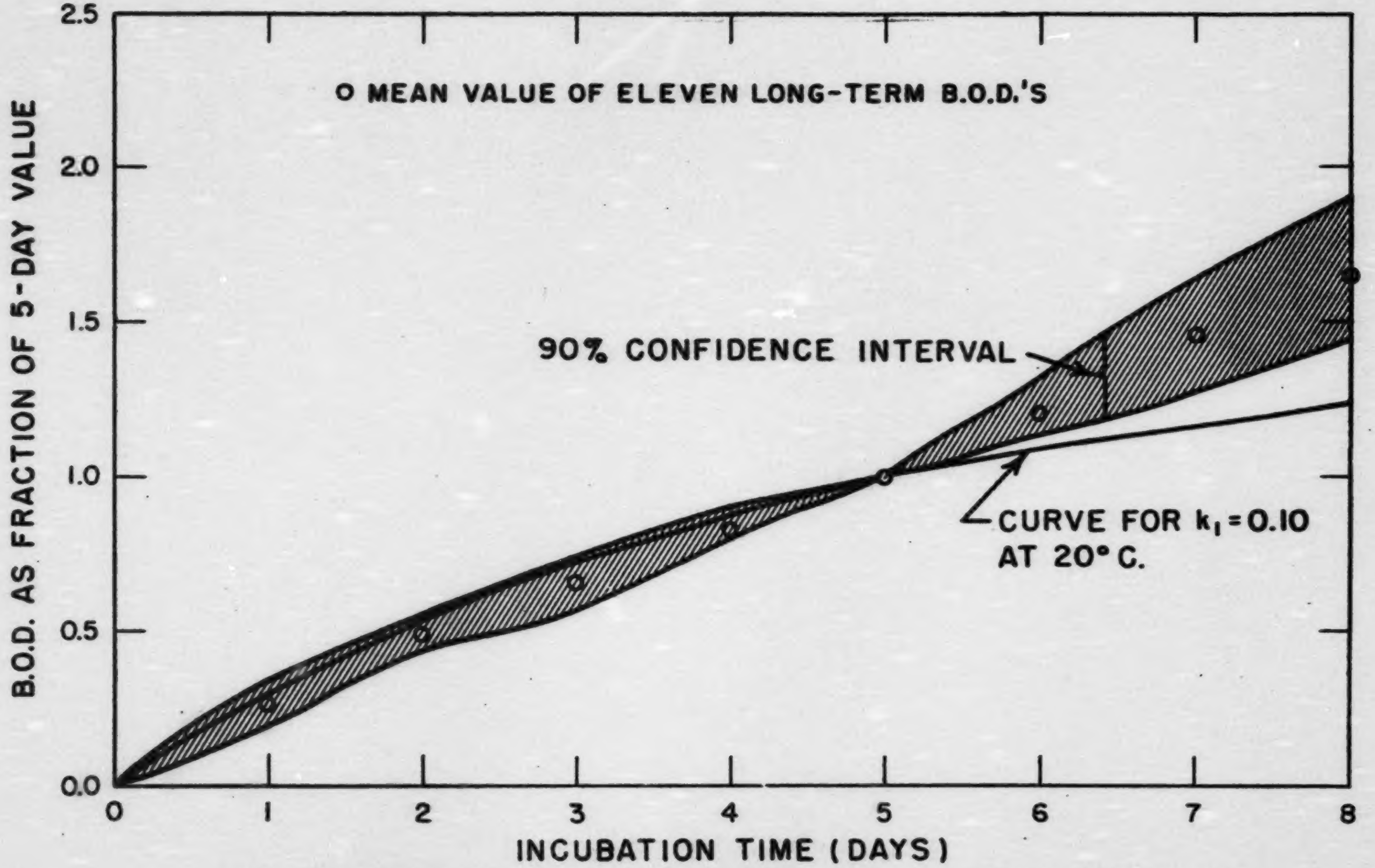
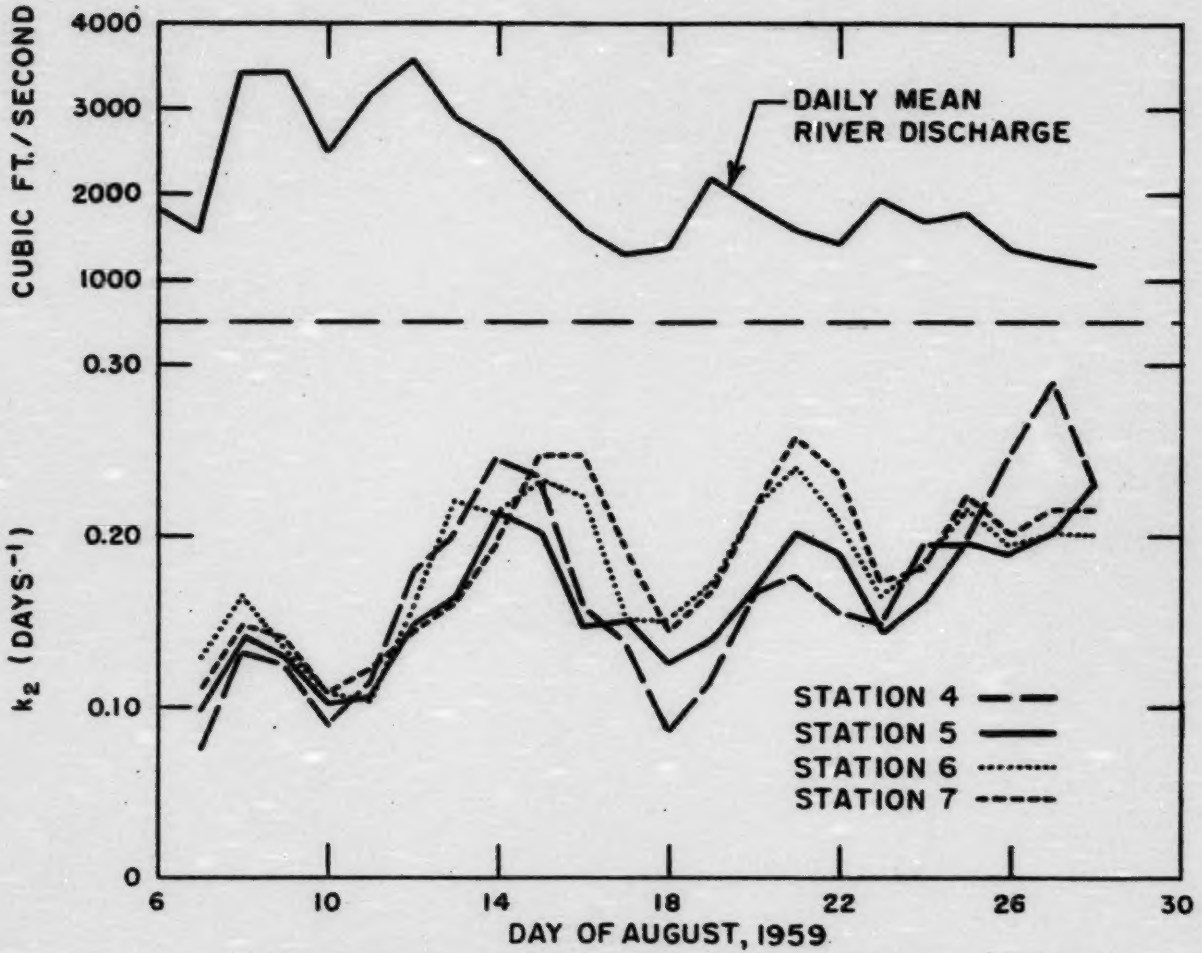
*Since the stream waste load is being constantly replenished by "fresh" BOD, it is likely that the behavior of a sample in the first few days of incubation is more representative of stream conditions than is its behavior after an extended incubation period. This would not necessarily be true in a nontidal stream.



COMPARISON OF LONG-TERM B.O.D. RESULTS WITH THEORETICAL CURVE FOR $k_1 = 0.10$

FIGURE 47



REAERATION RATE CONSTANTS CALCULATED FROM DAILY MEANS

FIGURE 48

Table XXV

Long-Term BOD Results

Time	Sample Taken at Station Number:										
	0	1	2	3	4	5	6	7	8	Fort Washington	Marshall Hall
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	0.40	1.54	0.49	0.60	0.42	1.18	1.26	0.88	0.69	0.27	1.27
2	1.02	1.99	0.98	1.10	0.74	1.64	1.58	1.68	1.63	2.80	2.49
3	0.90	2.10	1.06	1.63	1.00	2.84	2.52	2.40	2.53	3.74	3.45
4	1.88	2.60	1.49	1.95	1.78	2.98	2.70	2.54	3.29	4.53	4.48
5	2.02	2.88	1.56	2.30	1.96	4.10	2.94	3.82	4.58	5.14	5.37
6	3.20	3.02	1.84	2.22	2.20	5.08	4.02	4.58	6.11	5.64	6.34
7	3.66	3.14	1.98	2.85	3.54	-	5.56	-	7.53	5.90	6.83
8	-	3.27	2.21	3.27	3.74	9.78	-	8.40	8.47	6.16	7.58
9	5.58	-	-	-	-	-	7.36	-	8.48	6.63	8.37
10	-	-	-	-	3.92	13.2	-	13.3	8.53	6.92	8.85
11	6.50	-	-	-	-	-	9.70	-	-	-	-
12	-	-	-	-	7.00	16.5	-	-	-	-	-
13	7.90	-	-	-	-	-	11.7	16.2	-	-	-
Sample Concentration(%)	50	100	100	100	50	50	50	50	100	100	100

Table entries are calculated BOD values

Table XXVI

Computation of k_2 from Streeter-Phelps Formulation

Station 4

Date	L	$\frac{\Delta D}{\Delta t}$	D	k_2 (day^{-1})	k_2 (day^{-1}) Running Mean
6					
	4.20	+0.71	5.36	0.051	
7					0.075
	3.87	-0.06	5.69	0.099	
8					0.133
	3.65	-0.89	5.22	0.166	
9					0.125
	3.19	+0.06	4.80	0.083	
10					0.090
	3.42	-0.03	4.82	0.096	
11					0.115
	3.68	-0.31	4.65	0.133	
12					0.180
	3.83	-0.93	4.03	0.226	
13					0.203
	4.17	-0.12	3.50	0.179	
14					0.245
	4.42	-0.73	3.08	0.310	
15					0.233
	4.71	+0.51	2.96	0.155	
16					0.162
	5.25	+0.48	3.46	0.169	
17					0.139
	4.49	+0.57	3.99	0.108	
18					0.085
	4.14	+0.84	4.69	0.062	
19					0.116
	4.74	-0.22	5.00	0.169	
20					0.167
	5.01	-0.02	4.88	0.164	
21					0.176
	5.64	-0.05	4.85	0.188	
22					0.154
	6.21	+0.82	5.23	0.119	
23					0.148
	6.40	+0.03	5.65	0.177	
24					0.195
	5.53	-0.62	5.36	0.213	
25					0.196
	5.06	-0.19	4.96	0.178	
26					0.249
	5.96	-1.03	4.35	0.320	
27					0.291
	6.83	+0.14	3.90	0.261	
28					0.227
	6.93	+0.63	4.29	0.192	
29					

Table XXVI (Continued)

Computation of k_2 from Streeter-Phelps Formulation

Station 5

Date	L	$\frac{\Delta D}{\Delta t}$	D	k_2 (day^{-1})	k_2 (day^{-1}) Running Mean
6					
	5.75	+1.00	5.70	0.063	
7					0.098
	5.22	-0.21	6.10	0.133	
8					0.139
	4.34	-0.53	5.73	0.145	
9					0.128
	3.82	-0.16	5.38	0.111	
10					0.101
	3.45	-0.06	5.27	0.091	
11					0.107
	3.49	-0.33	5.08	0.123	
12					0.149
	3.95	-0.60	4.61	0.175	
13					0.165
	4.33	-0.13	4.25	0.154	
14					0.213
	4.53	-0.84	3.76	0.271	
15					0.200
	4.93	+0.57	3.63	0.128	
16					0.147
	5.39	+0.32	4.07	0.166	
17					0.151
	5.48	+0.58	4.52	0.136	
18					0.125
	5.83	+0.76	5.19	0.114	
19					0.139
	5.77	0.00	5.57	0.164	
20					0.173
	5.94	-0.13	5.51	0.181	
21					0.202
	6.48	-0.34	5.27	0.222	
22					0.192
	6.65	+0.43	5.32	0.162	
23					0.143
	7.08	+0.87	5.97	0.124	
24					0.164
	6.35	-0.56	6.12	0.204	
25					0.197
	6.05	-0.28	5.70	0.189	
26					0.191
	6.52	-0.07	5.53	0.192	
27					0.203
	6.48	-0.27	5.36	0.213	
28					0.232
	6.86	-0.40	5.02	0.251	
29					

Table XXVI (Continued)

Computation of k_2 from Streeter-Phelps Formulation

Station 6

Date	L	$\frac{\Delta D}{\Delta t}$	D	k_2 (day^{-1})	k_2 (day^{-1}) Running Mean
6					
	5.88	+0.80	5.85	0.079	
7					0.129
	5.96	-0.57	5.97	0.179	
8					0.165
	4.93	-0.34	5.51	0.150	
9					0.135
	4.28	-0.14	5.27	0.119	
10					0.108
	4.09	+0.09	5.25	0.096	
11					0.104
	4.12	-0.09	5.24	0.111	
12					0.159
	5.37	-0.62	4.89	0.207	
13					0.221
	5.56	-0.55	4.31	0.234	
14					0.214
	5.20	-0.06	4.00	0.194	
15					0.234
	5.71	-0.39	3.78	0.273	
16					0.224
	5.75	+0.46	3.81	0.175	
17					0.152
	5.77	+0.77	4.43	0.130	
18					0.150
	6.26	+0.34	4.98	0.169	
19					0.174
	6.36	+0.16	5.23	0.179	
20					0.216
	6.81	-0.47	5.08	0.252	
21					0.240
	7.76	+0.22	4.95	0.228	
22					0.211
	7.94	+0.51	5.32	0.194	
23					0.167
	7.78	+0.91	6.03	0.139	
24					0.185
	7.02	-0.70	6.13	0.231	
25					0.217
	6.29	-0.33	5.62	0.202	
26					0.195
	6.38	-0.03	5.44	0.188	
27					0.202
	6.78	-0.18	5.33	0.216	
28					0.202
	6.76	+0.15	5.32	0.188	
29					

Table XXVI (Continued)

Computation of k_2 from Streeter-Phelps Formulation

Station 7

Date	L	$\frac{\Delta D}{\Delta t}$	D	k_2 (day^{-1})	k_2 (day^{-1}) Running Mean
6					
	6.48	+0.74	5.92	0.097	
7					0.111
	6.01	+0.08	6.33	0.125	
8					0.148
	4.79	-0.82	5.96	0.171	
9					0.140
	4.34	0.00	5.55	0.108	
10					0.109
	4.25	-0.03	5.53	0.109	
11					0.121
	4.37	-0.25	5.40	0.132	
12					0.154
	4.77	-0.51	5.02	0.175	
13					0.162
	5.02	-0.03	4.74	0.149	
14					0.197
	5.07	-0.77	4.35	0.245	
15					0.249
	5.62	-0.34	3.79	0.253	
16					0.249
	6.56	+0.28	3.76	0.244	
17					0.194
	6.60	+0.96	4.38	0.143	
18					0.145
	6.35	+0.57	5.15	0.147	
19					0.171
	6.61	-0.03	5.41	0.195	
20					0.216
	6.90	-0.28	5.26	0.231	
21					0.258
	7.74	-0.41	4.92	0.285	
22					0.234
	8.63	+0.95	5.19	0.183	
23					0.173
	8.95	+0.97	6.15	0.162	
24					0.184
	7.81	-0.25	6.51	0.206	
25					0.226
	6.42	-0.99	5.89	0.245	
26					0.202
	6.90	+0.45	5.62	0.159	
27					0.217
	7.21	-0.82	5.43	0.275	
28					0.216
	6.95	+0.61	5.33	0.156	
29					

It is immediately evident from this figure that there are consistent changes in k_2, some of which appear to be related to the river discharge. There is also an apparent upward trend in k_2 during the survey period. Since k_2 is an empirical constant and is actually a "catch-all" which includes the effects of any and all drivers which tend to add oxygen to the stream, it is difficult to attach any significance to this. It may be noted, however, that there was an upward trend in the algal population during the survey period. This trend might be related to algal oxygen production.

It can be seen, however, that there is an immediate increase in k_2 upon an increase in discharge, and that k_2 reaches a maximum 2 to 4 days after the peak discharge. Some crude estimates of the effects of river discharge on k_2 can be made from these results. The mean k_2 value on August 7 for the four stations is 0.103, while the mean of the maximum reached in the period from August 12 to August 16 is 0.235. If the change in k_2 is attributed solely to the effects of the 2,000 cfs increase in discharge, then it may be calculated that the change in k_2 permits a reduction in the oxygen deficit required to maintain a constant rate of reaeration in the system.

This can be done most simply by assuming that the deoxygenation and reoxygenation processes are in balance; that is, $k_1L = k_2D$. This is the condition required for operation of the system at its waste assimilation capacity. If k_1L is assumed fixed, the net increase in D.O. that will occur with an increase in k_2 can be calculated, assuming that the D.O. will increase until the processes of deoxygenation and reoxygenation are again in balance. The mean oxygen deficit at these four stations can be used as a basis for calculation.

$D_1 = 5.03$

when

$k_2 = 0.103,\ k_2D_1 = 1.193 = k_1L$

for

$k_2 = 0.235$ and $k_1L = 1.193,$

$k_2D_2 = 0.541\ D_2 = 1.193$

$D_2 = 2.21$ ppm

net D.O. increase = 5.03 -2.21 = 2.82

This is equivalent to an increase of 1.41 ppm D.O. per 1,000 cfs increase in river discharge. Since this value includes algal oxygen production and should therefore be high, it may be concluded that the results derived from the spectral analysis of the field survey data are consistent with this form of analysis.

A deoxygenation rate constant can also be deduced from the spectral results. In Table XVI are given the responses of D.O. to stream BOD at each stream station. The total stream BOD is composed of two parts: (1) dilution of each day's waste discharge, and (2) summation of the total unoxidized waste load remaining in the reach from the total load discharged over a long period of time. Each daily waste load is discharged into the quantity of water which flows by the outfall in one tidal cycle. This volume is equivalent to the tidal prism which, from Figure 45, is 0.425×10^9 feet cubed at the Blue Plains outfall.

An estimate of the amount of this load lost from the reach can be obtained from Table XVI. Because of the nature of the BOD determination, one (1) ppm D.O. consumed should equal one (1) ppm BOD exerted. Table XVI shows that the actual oxygen consumed is considerably less. For Stations 4 through 8, the mean D.O. response to BOD is 0.377 ppm D.O. per ppm BOD. This can be regarded as a measure of the turbulent mixing and flushing that is occurring; that is, of every ppm of BOD measured in the stream, 0.623 ppm is lost because of mixing and flushing out of the reach. The total amount of BOD that stays in the reach from a given waste load discharge can be estimated from Table XVII for Stations 4 through 8. This is:

$$4.35 \times 10^{-5} \ \frac{\text{ppm BOD}}{\text{lbs./day BOD}}$$

A deoxygenation rate constant can be calculated with these values. A daily waste load of 100,000 pounds of BOD_5 is assumed; the actual magnitude does not matter, for it cancels out the calculations.

Initial concentration caused by dilution =

$$\frac{100 \times 10^3 \ (10^6)}{(0.425 \times 10^9)(62.4)} = 3.77 \text{ ppm } BOD_5$$

Amount remaining of each day's load =

$$(0.377)(3.77) = 1.42 \text{ ppm } BOD_5$$

The total concentration of BOD_5 in this reach is:

$$(4.35 \times 10^{-5})(1 \times 10^5) = 4.25 \text{ ppm } BOD_5$$

The expression for the sum of a geometric progression may now be used.

$$4.35 = \frac{1.42}{1-r}, \text{ where } r = 10^{-k_1 t}$$

$$r = 0.6735$$

Since t = 1 day, $r = 10^{-k_1}$, and $-k_1 = \log_{10} 0.6735 = 0.17$.

This is the deoxygenation rate constant at 29°C., the mean temperature at these stations. The value may be converted to 20°C. by using the conversion:

$$k_T = k_{20} \times 1.047^{(T-20)}$$

When this is done, a value for k_1 at 20°C. of 0.11 is obtained. This is in very good agreement with what the long-term BOD's indicate.

VECTOR DIAGRAMS OF STREAM D.O. AND RIVER DISCHARGE

A check on the accuracy of these estimates may also be obtained from the daily mean values of D.O. and river discharge. If the daily mean D.O. is plotted as a function of river discharge and a line connecting sequential values is drawn, the vectorial plots in Figures 49 and 50 are produced. Similar graphs are obtained for the remaining stations. These graphs show that, while the maximum discharge occurred on August 12, the maximum D.O. did not occur until the 15th or 16th, a delay of 3 to 4 days.

It can also be seen that the plotted values form a closed curve, indicating a certain amount of consistency in the mechanism responsible. The curve is of generally elliptical shape; this type of behavior is a typical result of the interaction of two sinusoidally varying parameters. The river discharge spectrum exhibits only long-period effects; but the interaction of river discharge and the tide could result in a sinusoidal energy flow of a period short enough to be noticeable in these records. The geometry of the curves in Figures 49 and 50 might provide some clues to the nature and periodicity of the nonlinear interactions of tide and river discharge.

An estimate of the effect of river discharge on D.O. may be obtained by attributing the increase in D.O. from the 7th through the 16th of August to the increase in river discharge occurring during the same period. This results in the factors presented in Table XXVII.

Table XXVII

Effect of River Discharge on D.O. as Determined from Daily Means

Station	Total D.O. Change (ppm)	Total Discharge Change (cfs)	$\frac{\text{ppm D.O.}}{\text{1,000 cfs}}$
0	1.24	1,980	0.63
1	1.23	1,980	0.62
2	2.18	1,980	1.10
3	2.95	1,980	1.49
4	2.81	1,980	1.42
5	2.69	1,980	1.36
6	2.37	1,980	1.20
7	2.41	1,980	1.22
8	2.57	1,980	1.30
		Mean	1.15

These results check the factors presented in Tables XXII and XXIV to a reasonable degree. It should be noted that the results in Table XXVII include the effects of BOD and sunlight, while those in Tables XXII and XXIV do not.

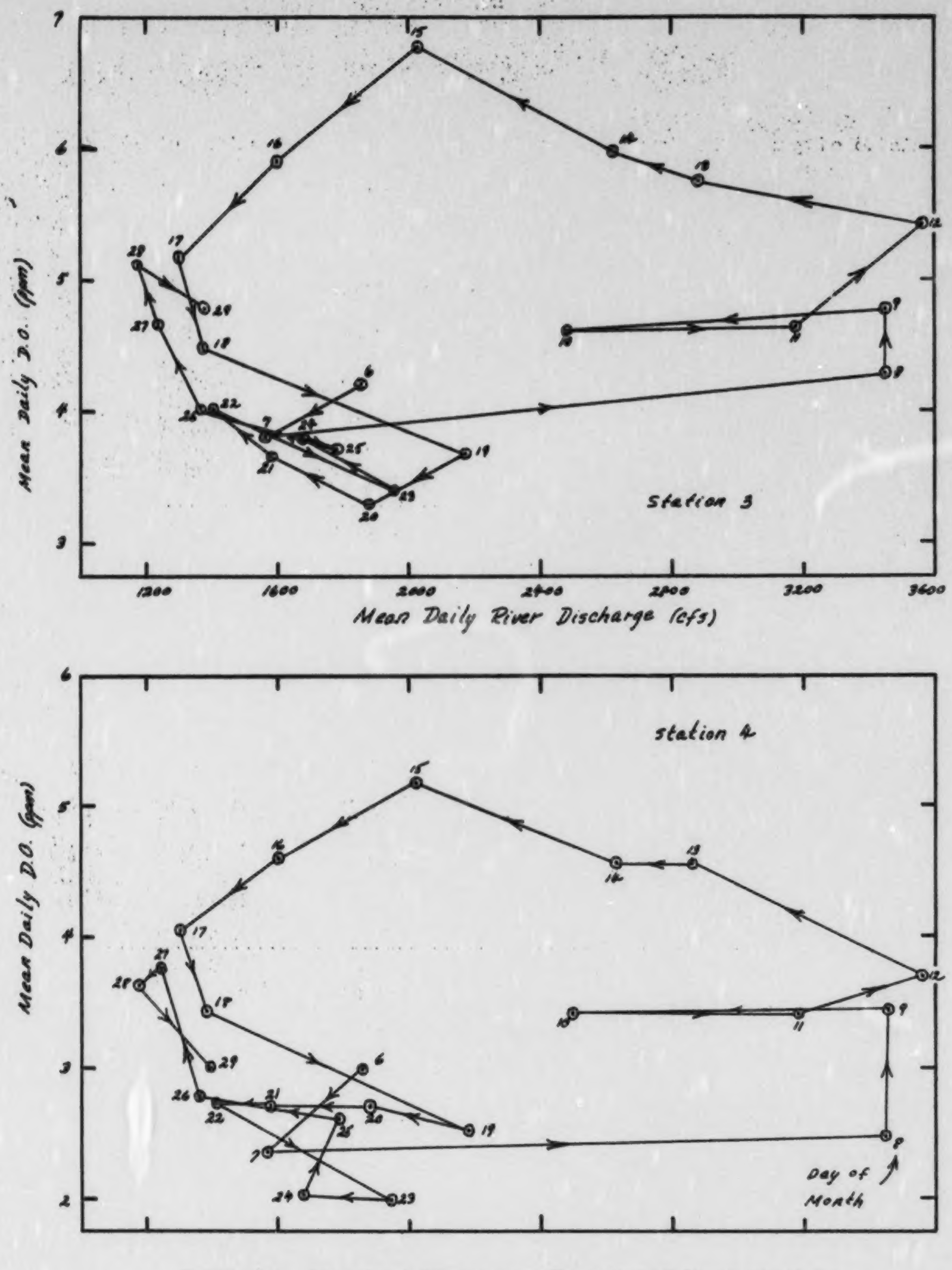


Figure 49. Dissolved Oxygen as a Function of River Discharge

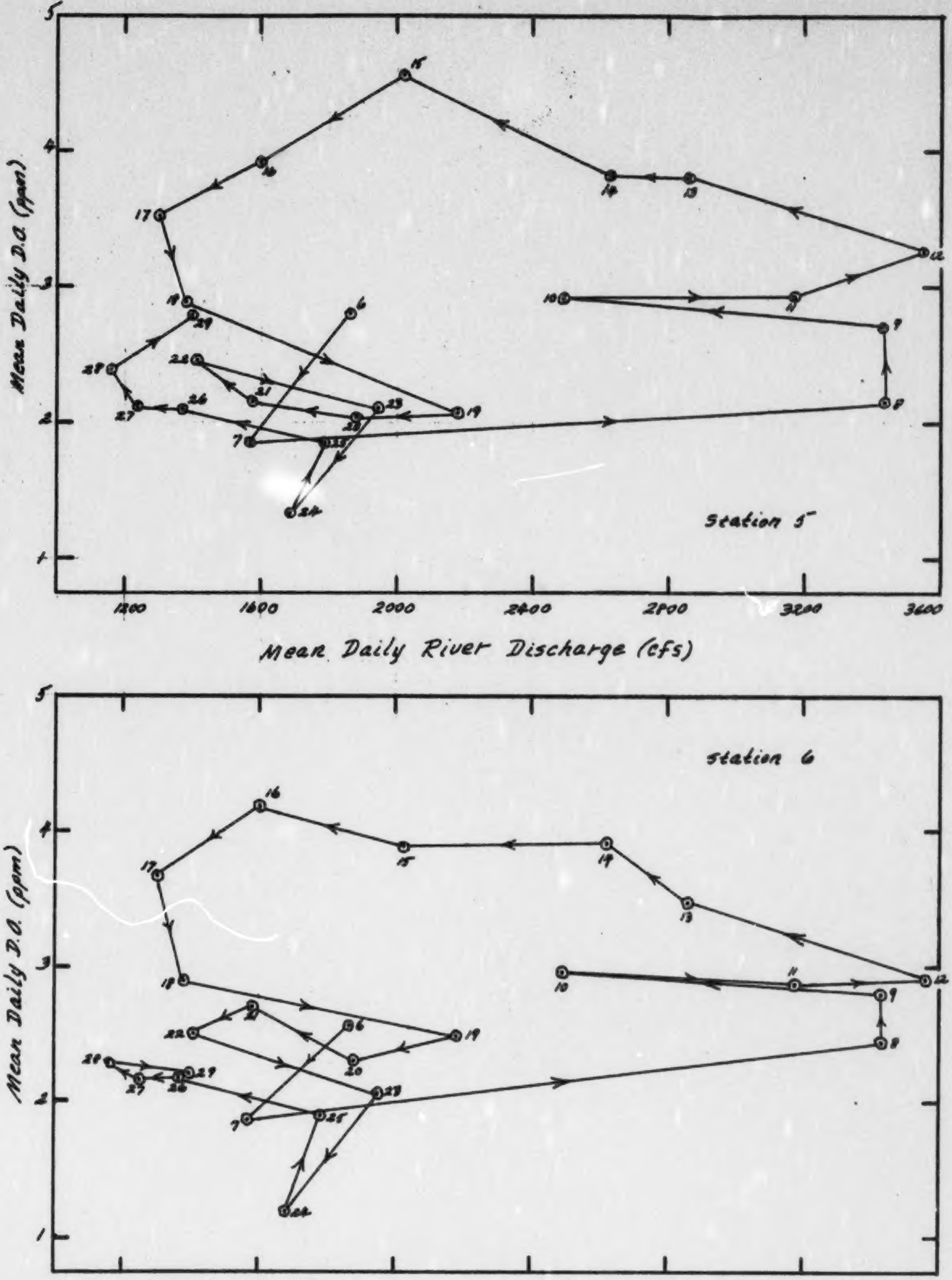


Figure 50. Dissolved Oxygen as a Function of River Discharge

In a nonlinear system such as this, there exists the possibility of occurrence of three phenomena: resonance, damping, or a limit cycle. This means that there may be conditions in which the turbulence would reach tremendous levels in comparison to the river discharge related to it, or the turbulence may be greatly suppressed, or increased or decreased discharge may have little or no effect on the turbulence. If a resonating system could be achieved, there would be an enormous increase in the waste assimilation capacity of the system. It might be possible to develop such a condition by regulating the river discharge to a harmonic of the tidal period. Detailed theoretical study and some model experiments would be necessary before any positive recommendations could be made.

ESTIMATION OF WASTE ASSIMILATION CAPACITY

METHOD OF COMPUTATION

The dissolved oxygen criteria for stream classification as developed by the Interstate Commission on the Potomac River Basin are considered to be reasonable objectives. For minimum sanitary condition these criteria require the maintenance of a monthly average D.O. of at least 4 ppm, and an absolute minimum D.O. of 2 ppm as shown in Table XXVIII. The waste assimilation capacity is defined to be the quantity of daily waste discharge, as measured by BOD_5, which will produce no less than the minimum monthly average D.O. objective chosen for a specific stream.

The Interstate Commission on the Potomac River Basin has set a monthly average D.O. objective of not less than 5 ppm for the Potomac River estuary from the Key Bridge to Fort Washington. With the diurnal fluctuations in D.O. to be expected in the estuary with present waste loadings, an absolute minimum D.O. of about 3 ppm may be expected if the 5 ppm objective is achieved.

The waste assimilation capacity of the Potomac River at Washington for the survey period may be calculated from the results discussed in the previous section. All of these results are based on variance from the mean value, except for the stream BOD concentration. Therefore, the calculations must be based on changes from the mean values of D.O. and river discharge which occurred during the field study.

TABLE XXVIII

INTERSTATE COMMISSION ON THE POTOMAC RIVER BASIN

Minimum Water Quality Criteria for Streams in the Potomac River Basin

Approved 8 August 1946

Parameter	CLASS A Drinking Water (No treatment except cl.)	CLASS B Bathing Fish Life	CLASS C Domestic Water Supplies (Before complete treatment) Industrial Process Water	CLASS D General Sanitary Condition (To prevent nuisance)
Coliform Bacteria MPN per 100 ml	0 - 50	Mo. avg. 50 - 500 Max. not over 1000	Mo. avg. 500 - 5000	------
Color, ppm	0 - 10	20 (desirable)	Amt. of color & turbidity allowed which can be removed by standard equipment & practices.	------
Turbidity, ppm	0 - 10	40 (desirable)	------	------
pH	6.0 - 8.0	6.0 - 8.5	6.0 - 8.5	6.0 - 8.5
5-Day BOD, ppm	------			
Mo. avg., ppm	------	1.5	2.0	3.0
Max. obs., ppm	------	3.0	4.0	5.0
D.O., ppm	------			
Mo. avg., ppm	7.5	6.5	6.5	4.0
Min. obs., ppm	6.5	5.0	5.0	Min. daily avg. 3.0 Absolute min. 2.0

Other Conditions

Same all classes: No toxic substances, oils, tars, or free acid at any time. No floating solids or debris, except from natural sources.

Classes A, B, C: No taste or odor producing substances. No sludge deposits.

Class D: Slight localized sludge deposits allowed, if unpreventable. No offensive odors.

NOTE: Criteria to be used only in conjunction with a sanitary survey as a guide in determining minimum water quality for various classes of water use listed. It is intended that these criteria should apply to conditions which are expected to prevail for the major part of the time.

The estimates of waste assimilation capacity are based on the stations where the greatest D.O. depletion occurred during the survey. This was in the reaches represented by Stations 0, 4, 5, 6, 7, and 8. This reach, including the Anacostia River and the Potomac from Haines Point to Fort Foote, actually showed quite uniform D.O. depletion. The means all fell within one (1) ppm of each other. The mean BOD's in this reach were all within 2.4 ppm of each other. Within this reach, the worst conditions prevailed at Stations 5, 6, 7, and 8. The mean D.O.'s and mean BOD's at these stations were quite uniform; that is, the mean D.O.'s were within 0.3 ppm of each other and the mean BOD's were within 1.8 ppm of each other. It will be assumed that the reach represented by Stations 5, 6, 7, and 8 will also represent the lowest D.O. reach within the range of discharges for which the waste assimilation capacity is estimated. The factors which will apply within this reach are assumed to be the arithmetic mean of the values obtained at each of these stations. The factors so obtained are these:

$$\frac{\text{ppm BOD}}{\text{lbs./day BOD}} = 4.6 \times 10^{-5} \qquad \frac{\text{ppm D.O.}}{\text{ppm BOD}} = 0.38$$

Mean D.O. = 2.69 ppm

Mean River Discharge = 2,000 cfs

Mean Waste Load = 96,500 pounds per day of BOD_5

The computation of the waste assimilation capacity for the survey period may be formulated in this manner:

$\bar{C}$ = mean observed D.O. (ppm),

$\bar{W}$ = mean observed waste load (10^5 pounds per day),

$\bar{Q}$ = mean observed river discharge (10^3 cfs),

Q = river discharge (10^3 cfs),

W_Q = waste assimilation capacity at river discharge, Q, and

C_Q = mean minimum D.O. at river discharge, Q.

Then

$$C_Q = (1.01)(Q-\bar{Q}) + [\bar{C} -(W-\bar{W})(4.7)(.375)].$$

By substituting the observed mean values and simplifying, this equation can be reduced to:

$$C_Q = 1.01\ Q + 2.36 -1.73\ W$$

For the survey period C_Q = 2.69 ppm. The waste assimilation capacities for this stream D.O. as calculated from the preceding equation are presented in Table XXIX. From these results and the response factors calaculated for this reach, values of the reaeration rate constants, k_2, can be estimated from the oxygen-sag formulation for each river discharge.

This calculation is made by requiring that, when the system is operating at its waste assimilation capcity, the rates of deoxygenation and reaeration are in balance; that is,

$$\frac{dD}{dt} = 0$$

and therefore

$$k_1 L = k_2 D.$$

In terms of the factors calculated for this reach of the system, k_2 can be calculated in this manner:

$$k_2 = \frac{(W \times 10^{-5})(4.6 \times 10^{+5})(.375)(.15)}{(.684)(7.77 -2.69)}$$

The values for k_2 so obtained are presented in Table XXIX and in Figure 51.

Table XXIX

Waste Assimilation Capacity
of the Potomac Estuary in August 1959 for a
Mean Stream D.O. of 2.69 ppm

River Discharge (cfs)	Waste Assimilation Capacity (lbs. BOD_5/day)	Reaeration Rate Constant k_2 (day^{-1})
800	28,000	.037
1,000	39,000	.051
1,500	69,000	.091
2,000	97,000	.128
2,500	127,000	.168
3,000	156,000	.206
3,500	185,000	.244
4,000	215,000	.284
4,500	244,000	.322
5,000	273,000	.360

The linear relationship of k_2 to river discharge of this discharge range may be the result of the assumptions of non-interaction among sunlight, corrected stream BOD, and the river-tide.* The factors used are average

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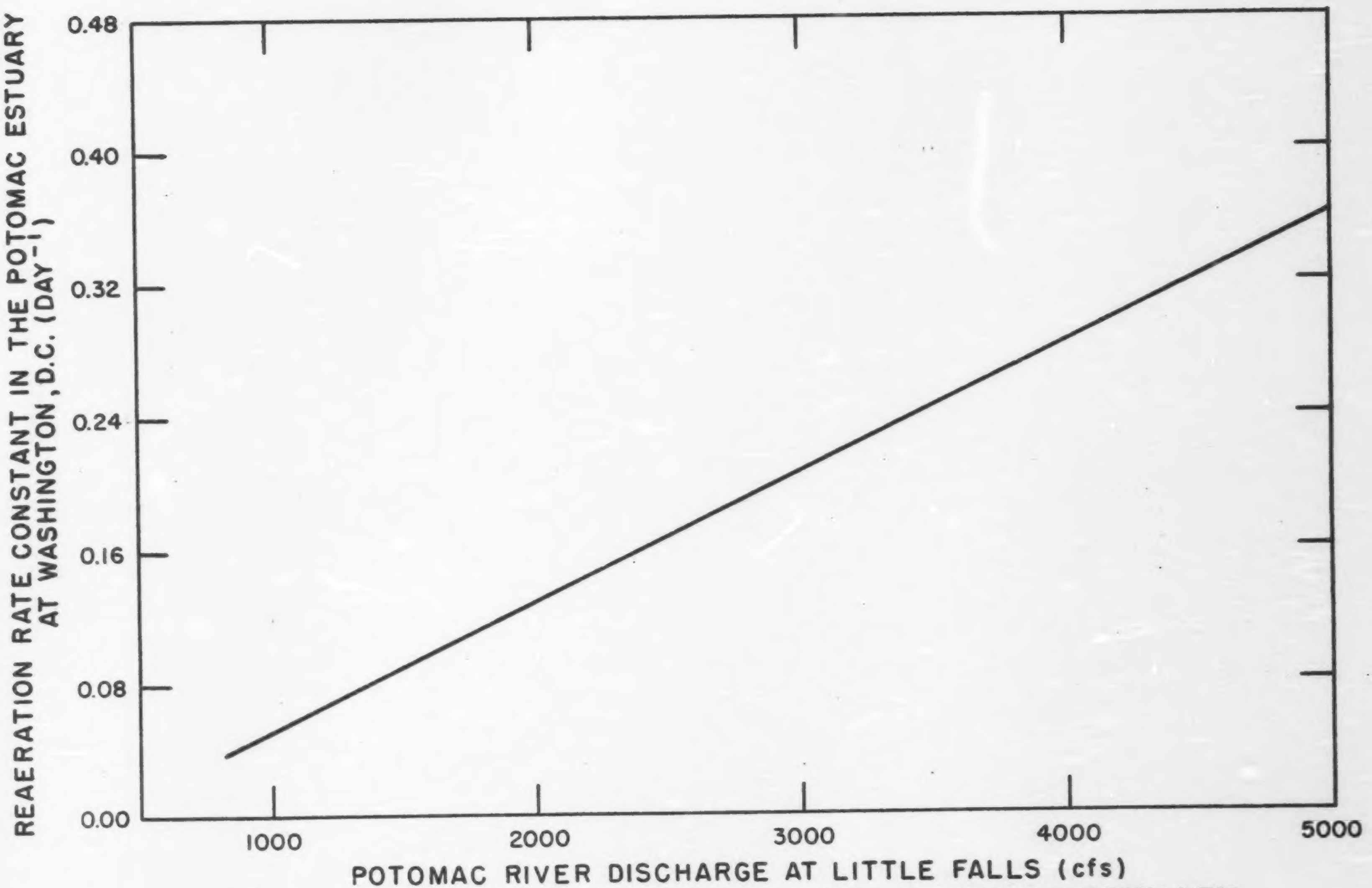
*If these assumptions are correct, then it may be deduced that the energy input from the river-tide to the turbulent regime is directly proportional to the river discharge, which appears reasonable over this range of discharges.



REAERATION RATE CONSTANT IN THE POTOMAC ESTUARY AS A FUNCTION OF RIVER DISCHARGE

FIGURE 51

values which have been computed empirically from data obtained over a discharge range of 1,200 to 3,600 cfs. It may be expected that the results are a reasonably good average representation of events occurring within this discharge range and probably give useful results for a limited range of extrapolation.

The values of k_2 as presented in Table XXIX can be used to estimate the waste assimilation capacity at the required D.O. level of 5.0 ppm, and at other levels. This is done from the equation used for calculating k_2 simply by substituting k_2 and the required D.O. level and then solving for W. These results are presented in Table XXX and Figure 52. These estimates of waste assimilation capacity may be regarded as typical of late summer conditions.

A linear result is also obtained here because the effects of waste discharge, river discharge, and sunlight have been assumed to act independently of each other. It is felt that this assumption is reasonably valid for the range plotted in Figure 52. Extrapolation to ranges much greater than this might be subject to serious and somewhat indeterminate error.

The sunlight would control the diurnal variance of the D.O. The maximum stream BOD which would occur with the loadings presented in Table XXX is about 13 ppm. If the curve in Figure 42 is extrapolated to this BOD value, the total variance is about .40 $(\text{ppm D.O})^2$. If this were all diurnal, it would be equivalent to a standard deviation of about 0.63 ppm D.O. Using the criterion of 1.6 standard deviations for the D.O. frequency distributions as developed previously, it may be found that deviations of more than 1.0 ppm

Table XXX

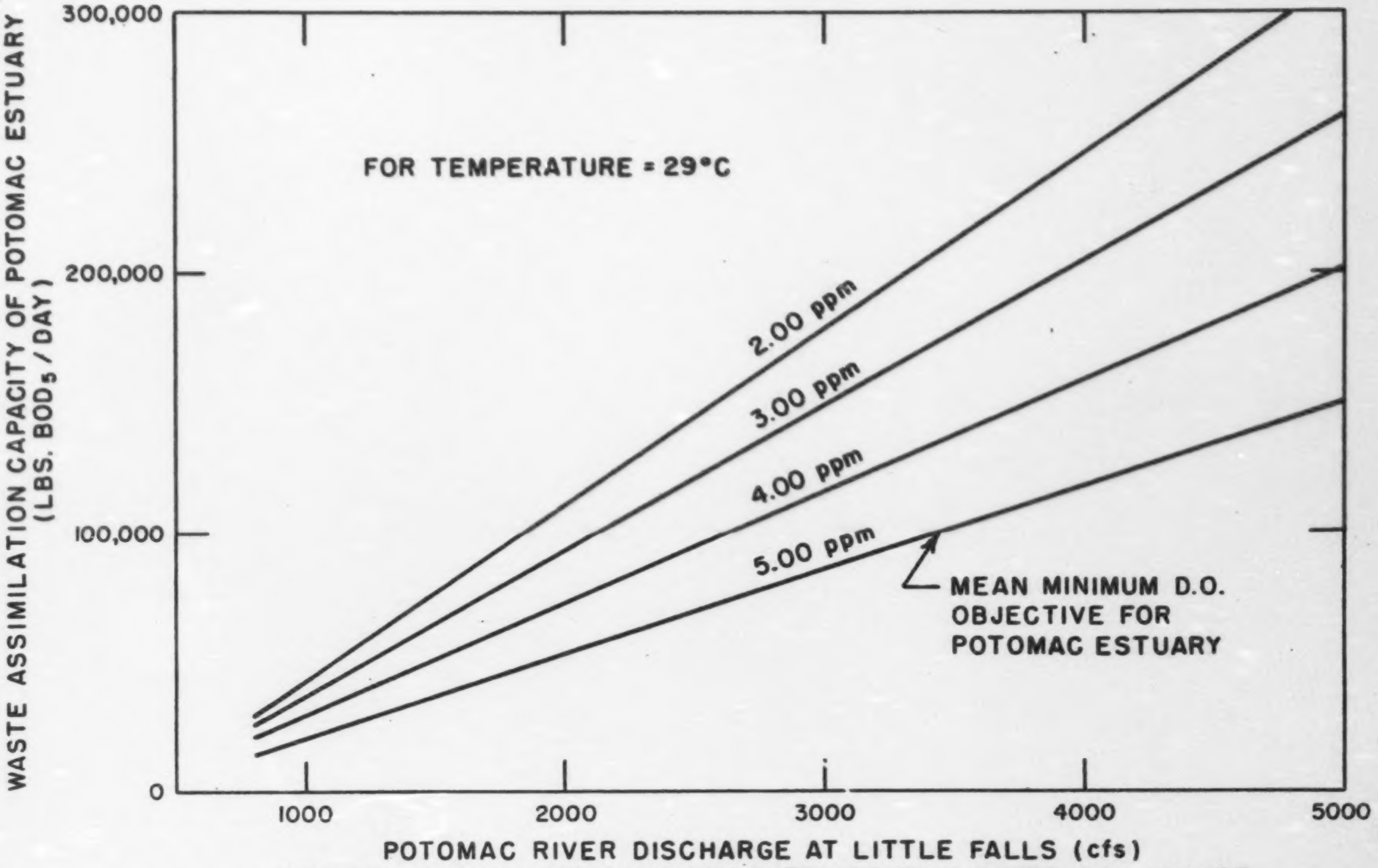
Waste Assimilation Capacity of the Potomac River at Washington, D. C.

River Discharge (cfs)	Waste Assimilation Capacity ($lbs. BOD_5/day$) for D.O. of:			
	5.0 ppm	4.0 ppm	3.0 ppm	2.0 ppm
800	15,000	21,000	26,000	29,000
1,000	21,000	29,000	37,000	44,000
1,500	38,000	51,000	64,000	78,000
2,000	53,000	73,000	92,000	110,000
2,500	69,000	94,000	120,000	140,000
3,000	85,000	120,000	150,000	180,000
3,500	101,000	140,000	170,000	210,000
4,000	117,000	160,000	200,000	240,000
4,500	133,000	180,000	230,000	280,000
5,000	149,000	200,000	260,000	310,000

Note: These values are for a mean river temperature of 29°C.

are highly improbable as a result of sunlight alone. Since the worst conditions have been computed in this manner, it may be assumed that the InCoPot (Interstate Commission on the Potomac River) absolute minimum D.O. value of 2.0 ppm can be met easily with these loadings and river discharges.

Estimates of waste assimilation capacity at temperatures other than 29°C. can be made by applying temperature conversion factor to the k_1 value used here and then computing the daily waste loads from the oxygen-sag equation. This has been done for a range of temperatures from 2 to 25°C. for mean minimum D.O.'s of 5, 4, and 3 ppm. The results are presented in Table XXXI. These are estimates of the total waste assimilation capacity of the estuary.



WASTE ASSIMILATION CAPACITY OF THE POTOMAC RIVER
AT WASHINGTON, D.C.
FIGURE 52

COMPARISON OF RESULTS WITH OTHER DATA

The estimated waste assimilation capacities may be compared for consistency of the predicted values with data obtained for periods other than the survey period upon which these results are based.

The largest body of measurements available on this reach of the river are those obtained from the routine sampling program carried out by the District of Columbia sewage treatment plant. Several river stations have been sampled from 1937 to the present. Samples have been taken once a week during the summer months and less frequently at other times of the year. All samples were taken between 8 a.m. and 3 p.m. Since these samples were not obtained at uniform intervals, they are not suitable for analysis by the methods of statistical dynamics. However, they may be examined for consistency with the results of this study.

In examining these data, there are several important points which should be kept in mind:

1. All the samples represent daytime conditions. This means that all these results are biased by the effects of sunlight. It has been demonstrated that sunlight has an effect on the stream D.O. which is roughly proportional to the BOD. Examination of results presented in Table XI shows that, for the reach represented by Stations 5, 6, 7, and 8, the approximate diurnal effects make up about 50 percent of the total variance caused by sun-

Table XXXI

Waste Assimilation Capacity at Several Temperatures

Discharge cfs	1000	2000	3000	4000	5000	
Temperature °C.						
2	260,000	660,000	1,050,000	1,450,000	1,840,000	Mean Minimum D.O. = 4.00 ppm
5	200,000	510,000	810,000	1,120,000	1,420,000	
10	134,000	340,000	540,000	740,000	940,000	
15	90,000	230,000	360,000	490,000	630,000	
20	60,000	150,000	240,000	330,000	420,000	
25	40,000	102,000	160,000	220,000	280,000	
2	290,000	730,000	1,160,000	1,600,000	2,030,000	Mean Minimum D.O. = 3.00 ppm
5	230,000	570,000	900,000	1,240,000	1,580,000	
10	150,000	380,000	610,000	840,000	1,070,000	
15	104,000	260,000	420,000	570,000	730,000	
20	72,000	180,000	290,000	400,000	500,000	
25	50,000	120,000	200,000	270,000	350,000	
2	240,000	600,000	950,000	1,300,000	1,700,000	Mean Minimum D.O. = 5.00 ppm
5	180,000	440,000	700,000	970,000	1,200,000	
10	114,000	290,000	460,000	630,000	800,000	
15	74,000	187,000	296,000	410,000	520,000	
20	48,000	121,000	192,000	265,000	340,000	
25	31,000	78,000	124,000	170,000	216,000	

Table entries are lbs. BOD_5 per day.

light. Therefore, for conditions in which the stream BOD is around 6 to 8 ppm, the mean D.O. calculated from these data would be about 0.4 ppm higher than the actual mean D.O.

2. The stream BOD's are more likely to reflect short-term changes in the waste discharges than average waste loads representative of long-time averages. Comparison of the daily mean waste discharges in Table IV with the daily mean stream BOD's in Table VIII provides abundant evidence of this.
3. Changes in river discharge are not immediately reflected in the reaeration rate constant or in the stream D.O. A lag of at least several days has been noted in both k_2 and the stream D.O. for the range of discharges encountered during the survey period. The nature of this lag for other discharges has not been determined.
4. A comparison of the routine grab samples of the sewage treatment plant with the daily means of the six daily grab samples taken at the corresponding stream stations during this survey indicates that there is a consistent difference in technique in the BOD determination. The two sets of data for five of the stations are presented for comparison in Table XXXII.

The method chosen for checking the results of this study against the District of Columbia sewage treatment plant data has been to use the data to calculate k_2 values for a period of several months using the oxygen-sag equation and then to compare these with k_2 values predicted with the results

Table XXXII

Comparison of Daily Means Obtained in the Field Survey with Other Data

	District of Columbia Sewage Treatment Plant			Public Health Service Field Survey		
Day of August 1959	Temperature ($^\circ$C.)	DO (ppm)	BOD$_5$ (ppm)	Temperature ($^\circ$C.)	DO (ppm)	BOD (ppm)
Station 8						
12	26.8	2.0	2.4	27.2	2.85	4.68
19	29.7	3.5	3.8	29.8	3.21	6.87
26	29.7	0.8	3.4	29.9	2.44	4.60
Station 7						
12	27.1	2.9	2.8	26.9	2.82	3.14
19	29.6	2.1	3.6	29.9	2.22	4.40
26	29.5	1.7	2.3	30.2	2.22	4.33
Station 6						
12	27.6	3.9	2.9	26.7	2.92	3.08
19	30.1	2.0	1.9	30.0	2.48	4.53
26	29.2	1.7	2.7	30.1	2.17	4.25
Station 5						
12	25.7	2.7	2.0	26.3	3.27	2.50
19	29.9	1.6	3.1	29.9	2.08	4.28
26	28.5	2.6	2.7	29.9	2.09	4.54
Station 4						
12	25.4	3.2	1.4	26.2	3.70	2.57
19	29.7	2.0	3.2	30.0	2.52	3.26
26	29.3	2.0	2.3	29.9	2.79	3.71
Mean	28.5	2.3	2.7	28.9	2.65	4.05
	Results based on one grab sample each day in the daytime.			Results based on six grab samples each day at uniform intervals.		

of this study. While this is a very crude way of attempting to compare the calculated parameters, it should at least serve to demonstrate whether or not the predicted results are consistent with the scattered grab samples.*

The sequence chosen for examination is July through October 1960, at Station 8. For the purposes of this calculation it has been assumed that sequential samples represent linear changes in the variables concerned and that the samples taken represent the mean values at Station 8 for that day. The results of this study indicate that both of these assumptions may be questioned. The mean values of D.O. deficit and BOD between sequential samples and the change in oxygen deficit per day between these samples are used in the finite difference form of the oxygen-sag equation to calculate a mean k_2 value for this period. The mean river discharges for each week have also been computed. These results are presented in Table XXXIII and Figure 53. The effect of a single standard deviation of the observed BOD from the actual mean value for that day is indicated by the confidence bands on the estimated mean k_2.

These results indicate that there is a dependence of k_2 on river discharge and that this dependence is of the same magnitude as estimated from the results of this study. Comparison of absolute values is not justified because the k_2 values calculated from the sewage treatment plant data are once again "catchall" empirical constants, while the values predicted from the field study data have had many of the modifying influences removed. The latter are therefore more nearly representative of the river discharge effects.

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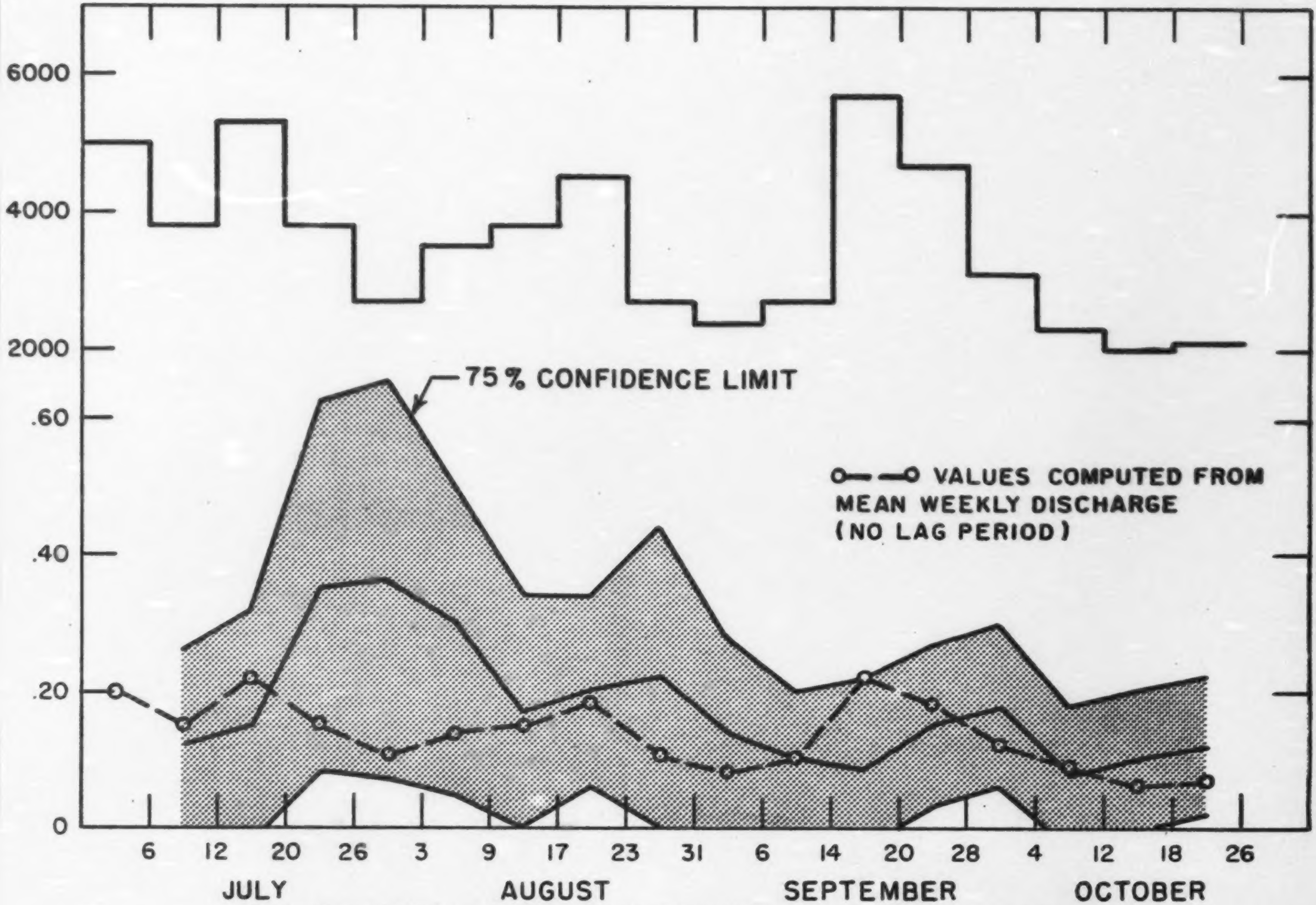
*If the waste assimilation capacity could have been calculated from these data, an expensive field study would not have been undertaken.

Table XXXIII

Reaeration Rate Constants Calculated from Weekly Grab Samples

Date	River Discharge (cfs)	Temperature (°C)	D.O. (ppm)	BOD (ppm)	k_2
	5000				
July 6, 1960		26.3	3.9	2.2	
	3800				.12
12		26.0	3.5	3.7	
	5300				.15
20		26.4	4.5	2.4	
	3800				.35
26		27.5	6.9	4.4	
	2700				.36
August 3, 1960		27.6	4.1	6.1	
	3500				.30
9		28.0	3.9	5.2	
	3800				.17
17		26.8	3.4	2.2	
	4500				.20
23		27.0	5.3	4.0	
	2700				.22
31		28.2	3.9	4.1	
	2400				.14
September 6, 1960		27.0	2.5	3.2	
	2700				.10
14		23.2	3.3	2.2	
	5700				.084
20		23.2	3.8	2.4	
	4700				.15
28		21.4	4.4	5.7	
	3100				.18
October 4, 1960		20.0	5.8	2.9	
	2300				.075
12		19.9	3.3	4.0	
	2000				.10
18		19.9	3.7	3.9	
	2100				.12
26		14.1	5.9	4.1	



REAERATION RATE CONSTANTS CALCULATED FROM D.C. SEWAGE TREATMENT PLANT DATA

FIGURE 53

The great range exhibited by the 75 percent confidence bands on k_2 is indicative of the usefulness of single grab samples in a system of this type.

SUPPLEMENT

POTOMAC RIVER BIOLOGICAL INVESTIGATION, 1959

INTRODUCTION

The following report concerns the biological investigation performed on the Potomac River in the vicinity of Metropolitan Washington, D. C., in August and September 1959. The description and location of each station and sampling point, the sampling procedure, and the results of the sampling are presented.

SURVEY

SAMPLING STATIONS

The stations designated by code numbers 1, 2, 3, 4, 5, 6, 7, and 8 are the regular sampling stations for the water quality study. The stations otherwise designated are added to permit a more complete biological coverage of the area. The sampling stations are identified in Table 1 and are shown on Figure 1.

Table 1

Sampling Stations

Station	Location
1	0.3 miles upstream from the Corps of Engineers boat dock on the Anacostia River.
1A	Quarter point from the right bank (USPHS looking upstream).
1B	Midstream.

Table 1 (Cont.)

Sampling Stations

Station	Location
1C	Quarter point from left bank.
0.0	Channel marker N" 2" directly opposite the Corinthian Yacht Club.
0.0A	15-25' south of the channel.
0.0B	Midchannel.
0.0C	15-25' north of the channel.
0.1	100-200' above the Key Bridge.
0.1A	15-25' north of the channel.
0.1B	Midchannel.
0.1C	15-25' south of the channel
2	The mouth and general area around a sewer discharging from the right bank 500 yards below the Key Bridge.
3	Mouth and general area where Rock Creek enters the Potomac River.
4	Sewer discharging 100' below the confluence of Rock Creek and the Potomac River.
4A	10-15' above the sewer and 15-20' from the bank.
4B	Directly in front of the sewer 15-20' from the bank.
4C	20-25' below the sewer and 15' from the bank.
0.2	Opposite the channel marker C" 15".
0.2A	15-20' from the concrete wall along the right bank.
0.2B	Midstream.
0.2C	15-20' west of the channel.

Table 1 (Cont.)

Sampling Stations

Station	Location
5	50' below the lower tip of Roosevelt Island.
0.3	Channel markers N" 4" and C" 3" off the lower tip of Haines Point.
0.3A	15-20' east of the channel.
0.3B	Midchannel.
0.3C	15-20' west of the channel.
6	20-25' west of the tip of Haines Point.
0.4	Channel marker C" 11" opposite the lower end of the Washington National Airport.
0.4A	15-20' east of the channel.
0.4B	Midchannel.
0.4C	15-20' west of the channel.
7	West of channel marker R" 2" at the mouth of Four Mile Run. 30' from the south shore.
0.5	Beneath aero tower just above Marburg Point.
0.5A	15-20' east of the channel.
0.5B	Midchannel.
0.5C	15-20' west of the channel.
0.5D	Approximately halfway between 0.5C and 0.5E.
0.5E	15-20' from the west bank
0.6	Directly opposite the sewage treatment plant outfall at Marburg Point.

Table 1 (Cont.)

Sampling Stations

Station	Location
0.6A	100-200' from the east bank near the outfall.
0.6B	15-20' east of the channel.
0.6C	Midchannel.
0.6D	15-20' west of the channel.
0.7	Channel marker N" 8" just below Goose Island.
0.7A	15-20' east of the channel.
0.7B	Midchannel.
0.7C	15-20' west of the channel.
8	Opposite the mouth of Hunting Creek on a line running northwest from Rosier Bluff toward the bridge crossing the mouth of the creek.
8A	15-20' east of the channel.
8B	West of the channel directly south of Jones Point.
8C	West of the channel and in the bay area.
0.8	100-200' above the channel marker C" 8" and beneath Rosier Bluff.
0.8A	15-20' east of the channel.
0.8B	Midchannel.
0.8C	15-20' west of the channel.
0.8D	300' west of the channel.
0.8E	500' west of the channel.
0.8F	700' west of the channel.

Table 1 (Cont.)

Sampling Stations

Station	Location
0.8G	900' west of the channel.
0.8H	100-150' from the west bank.
0.9	Channel marker C" 79" in the cable area.
0.9A	East of the channel 100-150' from the bank.
0.9B	Midchannel.
0.9C	15-20' west of the channel.
0.9D	300' west of the channel.
0.9E	200-250' from the left bank.
9	600-800 yards above the channel marker N" 76". The samples were collected at points on a line bisecting Piscataway Creek and running directly to Sheridan Point on the left bank.
9A	East of the channel directly north of Mockley Point.
9B	Midway between A and the channel.
9C	25-50' east of the channel.
9D	15-20' west of the channel.
9E	West of the channel; halfway to the west shore from D.
1.0	800 yards above the channel marker 67" and opposite Ferry Point.
1.0A	15-20' east of the channel.
1.0B	Midchannel.
1.0C	15-20' west of the channel.
1.0D	300' west of the channel.
1.0E	500' west of the channel.

PROCEDURE

Most of the bottom samples were obtained using an Ekman dredge, making one dredge haul for each sampling point. Stations 1 and 0.0 were exceptions; instead, a Petersen dredge was manipulated. At Stations 2 and 3 both dredges were used, but to no avail because of a hard, stony bottom.

At each of the stations located at or near channel markers, dredge hauls were made 15 to 25 feet outside each edge of the channel; several stations were located along one of the shore lines or in the vicinity of sewer outfalls. These were sampled above, below, and directly opposite the point at which they entered the Potomac River. In addition, extra sampling points were established at Stations 0.5, 0.8, 0.9, 9, and 10. The bottom animals that were collected were preserved in 5 percent formaldehyde for laboratory analysis. The bottom animals collected at all of the sampling points are shown in Table 2.

Several of the stations and sampling points to be described were sampled a few weeks previously by a State group. These stations were 0.5, 8, and 9. The State personnel involved were:

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Table 2

Kinds of Bottom Organisms Collected at Each Sampling Point

Station	Sludge Worms	Blood Worms	Segmented Entrychaeid Worms	Pearl Button Clams	Pearl Button Clam Shells	Fingernail Clams	Fingernail Clam Shells	Pond Snail Shells	Disc Snails	Operculate Snails	Moth Fly Larvae	Water Beetle Larvae	Nematode	Amphipod Fresh H_2O Shrimp
1A	x			x										
1B	x													
1C	x						x							
0.0A	x				x	x		x						
0.0B	x	x			x		x		x	x				
0.0C	x	x			x		x		x					
0.1A	x	x												
0.1B	x	x												
0.1C	x	x												
2	-	-	-	-	-	-	-	-	-	-	-	-	-	
3	-	-	-	-	-	-	-	-	-	-	-	-	-	
4A	x	x				x					x			
4B	x													
4C	x	x												
0.2A	x	x												
0.2B	x	x												
0.2C	x													
5	x	x												
0.3A	x	x	x			x								
0.3B	x	x												
0.3C	x	x												

Table 2 (Continued)

Kinds of Bottom Organisms Collected at Each Sampling Point

Station	Sludge Worms	Blood Worms	Segmented Entrychaeid Worms	Pearl Button Clams	Pearl Button Clam Shells	Fingernail Clams	Fingernail Clam Shells	Pond Snail Shells	Disc Snails	Operculate Snails	Moth Fly Larvae	Water Beetle Larvae	Nematode	Amphipod Fresh H_2O Shrimp
6	x	x												
0.4A	x					x								
0.4B	x	x		x		x								
0.4C	x	x				x								
7	x	x												
0.5A	x					x	x					x		
0.5B	x					x								
0.5C	x			x		x								
0.5D	x			x		x								
0.5E	x			x		x								
0.6A	x													
0.6B		x					x							
0.6C	x	x				x								
0.7A	x			x		x								
0.7B	x		x	x		x								
0.7C	x	x				x								
8A	x	x				x								
8B	x	x		x		x			x					
8C		x				x								

Table 2 (Continued)

Kinds of Bottom Organisms Collected at Each Sampling Point

Station	Sludge Worms	Blood Worms	Segmented Entrychaeid Worms	Pearl Button Clams	Pearl Button Clam Shells	Fingernail Clams	Fingernail Clam Shells	Pond Snail Shells	Disc Snails	Operculate Snails	Moth Fly Larvae	Water Beetle Larvae	Nematode	Amphipod Fresh H_2O Shrimp
0.8A	x		x	x	x	x	x							
0.8B	x	x		x		x								
0.8C	x	x		x		x								
0.8D	x	x	x		x	x				x				
0.8E	x			x		x			x	x				
0.8F	x				x		x							
0.8G	x				x		x							
0.8H						x								
0.9A	Bottom scoured clean			-	-	-								
0.9B	Bottom scoured clean													
0.9C	x	x					x							
0.9D	x	x		x		x								
0.9E	x	x				x							x	
9A	x			x										
9B		x		x		x								
9C	x	x	x			x								
9D	x			x						x				
9E		x		x		x								x
1.0A	x	x				x								
1.0B	x	x		x		x								
1.0C	x	x				x								
1.0D	x	x		x		x								
1.0E	x	x		x		x								

RESULTS

At 1A, the river bottom was composed of sand, silt, gravel, and organic debris which had a faint sewage odor. Sludge worms were abundant as were pearl button clam shells. There were only a few living clams in the collection; the rest of the whole shells were filled with silt and there were many half-shells. Bits of aluminum foil and soggy peanut shells completed the dredge haul.

The Petersen dredge was full of clay and small rocks that had an earthy odor at 1B. Sludge worms were the only bottom animals collected.

Clay, gravel, organic debris, and pieces of broken glass comprised the river bottom at 1C. Many soft, decaying fingernail clams were embedded in the clay; sludge worms were very much in evidence.

At 0.0A, the Petersen dredge was full of clay, silt, and organic debris; a slight sewage odor was detected. Many pearl button clam and pond snail shells filled with silt were mixed throughout the dredge haul. Sludge worms and fingernail clams were the only live organisms obtained.

The dredge was again full of clay and silt which had a strong, distinct sewage odor at 0.0B. Broken pearl button and fingernail clam shells were abundant. Disc snails (air breathers), operculate snails (gill breathers having an operculum), sludge worms, and blood worms were the living bottom animals collected.

0.0C was essentially the same as 0.0B. A distinct sewage odor was evident from the clay and silt. Disc snails, sludge worms and blood worms comprised the living organisms; many broken fingernail and pearl button clam shells were embedded in the clay and silt.

Clay characterized by a musty odor comprised the river bottom substrate at 0.1A. A relatively small number of sludge worms and blood worms were obtained.

Clay and a large quantity of organic debris characterized by a strong, musty, or earthy odor comprised the dredge haul at 0.1B. Sludge worms and blood worms were extremely plentiful.

0.1C was identical to 0.1B.

Because of the strong flow from the sewer at Station 2, it was impossible to hold the boat in sampling position at the mouth. Because of the extremely hard and stony river bottom in the general area of the sewer, it was impossible to collect bottom samples with either the Petersen or Ekman dredges.

The same situation prevailed at Station 3.

The river bottom at 4A was composed of clay, organic debris, pieces of newspaper, rags, cigar wrappers, and strands of hair. An oily sewage odor was very pronounced. Small rocks scattered over the bottom area hindered the sampling. Sludge worms, blood worms, fingernail clams, and moth fly larvae were obtained.

The river bottom at 4 B was silt, clay, and organic debris which had a definite oily sewage odor. Sludge worms were the only organisms collected.

At 4C, the dredge was full of silt, clay, and organic debris from which a strong, oily sewage odor emanated; toilet paper also appeared to be present. Sludge worms and blood worms were abundant.

The silt, clay, and organic debris at the river bottom of 0.2A had a definite oily odor. Sludge worms and blood worms were the only organisms in the dredge haul.

0.2B was identical to 0.2A.

The materials comprising the river bottom at Station 0.2C were silt, clay, leaves, and other organic material. The dredge haul was literally crawling with sludge worms.

Brownish mud with streaks of bona fide sludge throughout was found at Station 5; a very pronounced sewage odor was evident. Blood worms and sludge worms were the only bottom animals obtained.

The river bottom at 0.3A was silt and clay which had a musty, earthy odor. Segmented Entrychaeid worms, sludge worms, blood worms, and fingernail clams comprised the collection animal population.

The river bottom at 0.3B was identical to 0.2A; however, only sludge worms and blood worms were obtained in the dredge haul.

Silt, clay, and some organic debris comprised the substrate materials at 0.3C; a moderate sewage odor was evident. The animals were the same as those found in 0.3B.

The dredge was full of grayish clay that had a strong, definite sewage odor at Station 6. Blood worms and sludge worms were the only animals obtained.

Brownish mud and organic debris which had an earthy odor made up the river bottom materials at 0.4A. Sludge worms and fingernail clams were the only bottom animals found in the bottom mud and organic debris.

0.4B had physical bottom characteristics identical to 0.4A; blood worms and pearl button clams were found as well as sludge worms and fingernail clams.

At 0.4C the river bottom physical characteristics were identical to 0.4A and 0.4B. Sludge worms, blood worms, and fingernail clams were bottom organisms obtained.

At Station 7 the dredge was completely full of bona fide sludge which had a strong characteristic sludge odor. Sludge worms and blood worms were the sole macroinhabitants.

Mud and organic debris had a musty, earthy odor and constituted the dredge haul at 0.5A. Sludge worms, fingernail clams, and water beetle larvae constituted the living organisms collected; empty fingernail clam shells and cellophane were also embedded in the mud.

The physical bottom characteristics at 0.5B were the same as 0.5A; sludge worms and fingernail clams were collected.

A mixture of hair, cigarette filters, mud, and organic debris which had a sewage odor comprised the bottom substrate at 0.5C. Sludge worms, fingernail clams, and pearl button clams were the only organisms found.

0.5D and 0.5E were identical in physical bottom characteristics and the kinds of animals collected. The bottom was soft silt; fingernail clams, pearl button clams, and sludge worms were found living in the silt.

Unadulterated, pungent sludge filled the dredge at 0.6A; sludge worms were prolific as was hair and cellophane.

At 0.6B the dredge was full of a mixture of sludge, mud, and organic debris which had a typical sewage odor. Blood worms and a few emply fingernail clam shells were embedded in the sample.

Sludge worms, blood worms, and fingernail clams were found living in or on the mud and sludge river bottom at 0.6C.

The animal population at 0.6D was identical to 0.6C; however, the river bottom was mud which had a musty, earthy odor.

The river bottom at 0.7A was silt, sludge, and organic debris which had a penetrating sewage odor. Sludge worms, pearl button clams, and fingernail clams were obtained.

At 0.7B the river bottom was identical to 0.7A. Sludge worms, segmented Entrychaeid worms, pearl button clams, and fingernail clams were collected. Many of the clam shells were filled with silt.

A large amount of organic debris with some sludge comprised the river bottom at 0.7C. Numerous sludge worms, blood worms, and fingernail clams were living in or on the bottom materials.

The river bottom at 8A was soft silt; fingernail clams, sludge worms, and blood worms were collected.

Blood worms, sludge worms, fingernail clams, pearl button clams and disc snails were found living in or on the silt comprising the river bottom at 8B.

The river bottom at 8C was identical to 8B. Fingernail clams and blood worms comprised the animal life.

The river bottom was composed of brownish mud and organic debris which had a slight sewage odor at Station 0.8A. Sludge worms, segmented Entrychaeid worms, fingernail clams, and pearl button clams were collected; broken clam shells of each were also abundant.

Mud and little organic debris comprised the bottom materials at 0.8B. Sludge worms, blood worms, pearl button clams, and fingernail clams were the bottom fauna collected.

The bottom materials at 0.8C were identical to 0.8B. The fauna was the same also; however, hair was collected.

The dredge was full of silt, sludge, and organic debris at 0.8D. Large pearl button clam shells filled with silt were collected; fingernail clams, operculate snails, sludge worms, blood worms, and segmented Entrychaeid worms were also collected.

At 0.8E the bottom materials were the same as at 0.8D. Operculate snails, disc snails, pearl button clams, fingernail clams, and sludge worms were the bottom fauna collected.

The bottom materials at 0.8F were the same as 0.8D and 0.8E. Sludge worms were the only live organisms collected; broken pearl button clam and fingernail clam shells were embedded in the bottom materials.

0.8G was identical to 0.8F.

Mud and a large amount of organic debris comprised the bottom materials at 0.8H. Fingernail clams were the only organisms collected.

Strands of hair were abundant in all samples collected at Station 0.8.

At 0.9A and 0.9B the river bottom was scoured clean; no samples were obtained.

The river bottom at 0.9C was silt and a large amount of organic debris. Sludge worms, blood worms, and pieces of fingernail clam shells were obtained.

At 0.9D the bottom materials were silt, sludge, and organic debris; a moderate sewage odor was present. Sludge worms, blood worms, pearl button clams, and fingernail clams made up the bottom fauna that was collected.

Again at 0.9E the bottom materials were silt, sludge, and organic debris that had a moderate sewage odor. Nematodes, blood worms, sludge worms, and fingernail clams were botained in the bottom materials.

The river bottom was silt and was inhabited by sludge worms and immature pearl button clams at 9A.

Blood worms, fingernail clams, and immature pearl button clams inhabited the silt at 9B.

Blood worms, sludge worms, fingernail clams, and segmented Entrychaeid worms lived in the silt at 9C.

Operculate snails, pearl button clams, and sludge worms inhabited the silt at 9D.

At 9E the bottom area was silt inhabited by blood worms, fresh water shrimp, pearl button clams, and many fingernail clams.

Grayish mud and organic debris inhabited by blood worms, sludge worms, and fingernail clams were found at 1.0A.

The bottom materials at 1.0B were the same as at 1.0A; there were also a considerable amount of hair present in the sample. Pearl button clams, fingernail clams, sludge worms, and blood worms inhabited the bottom area.

The bottom materials at 1.0C were the same as at 1.0B; sludge worms, blood worms, and fingernail clams inhabited the area.

1.0D and 1.0E were the same as 1.0C.

DISCUSSION

Biological sampling of the Potomac River bed indicates considerable organic enrichment in the area sampled. Most of the bottom organisms collected are usually associated with high organic loads; sludge worms, blood worms, fingernail clams, and operculate snails are good examples of organisms associated with organic enrichment.

There was considerable material referred to as organic debris at many sampling points. This material consisted of leaves, twigs, pieces of tree bark, and various other bits or organic material. Strands of hair, the unidentifiable material that appeared to be pieces of toilet paper, and cellophane cigar wrappers were intermingled with the organic material at several of the sampling points. At many of the points the bottom mud or organic debris had a definite sewage odor, and in several instances pure unadulterated sludge was collected.

There was another indication of organic enrichment that was evident to the naked eye; even the uninitiated could sense that something was amiss.

During several weeks of the water quality survey, the Anacostia River and the Potomac River seemed to have the appearance and consistency of "pea soup." Microscopic examination of the water demonstrated a tremendous bloom of the blue-green alga, Anacystis sp., which is usually associated with conditions or organic enrichment and relatively high temperatures.

Based on the bottom sampling data and the visual observation of Anacystis sp., it is clearly indicated that a situation of considerable organic enrichment or pollution exists.